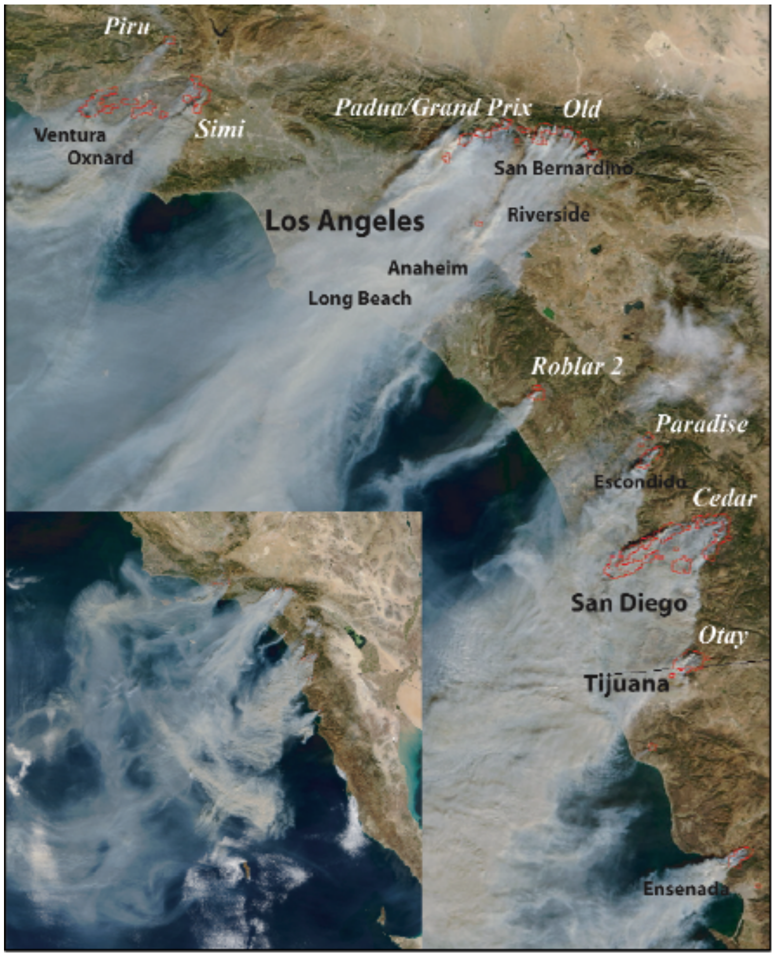
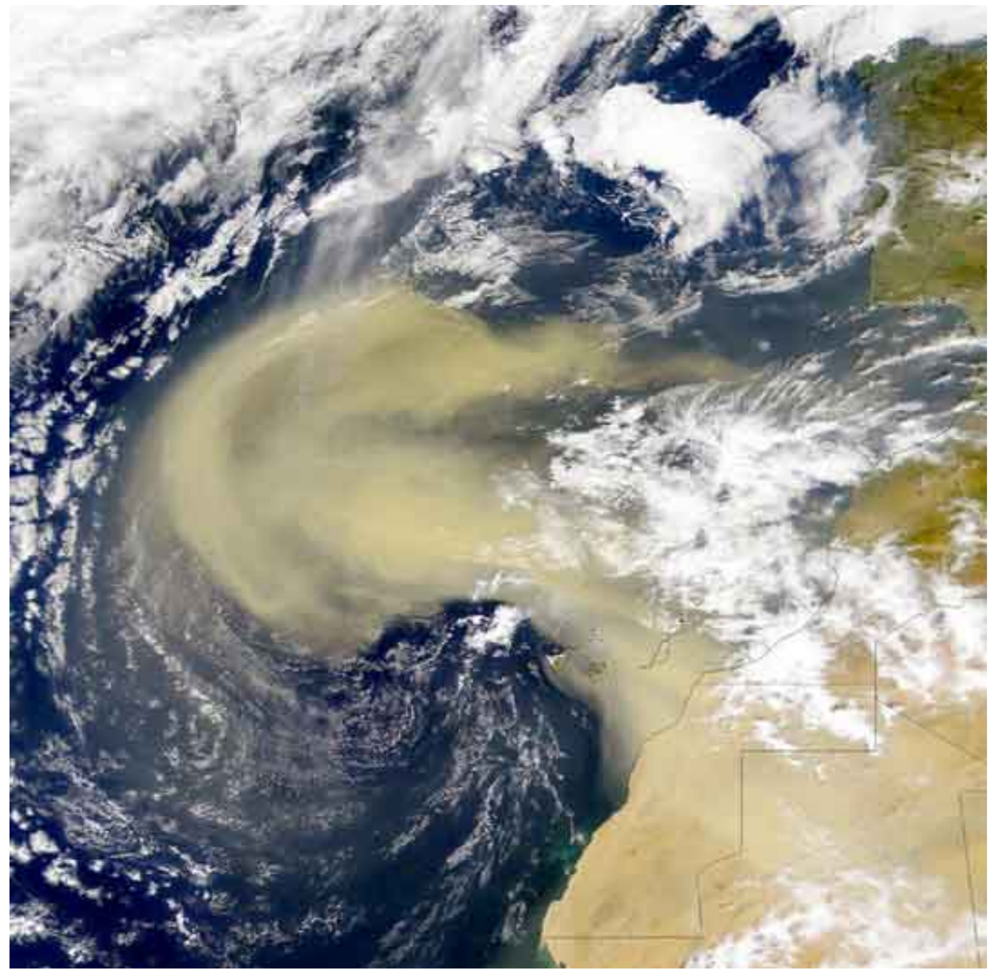
Laboratory Aerosol Characterization and More

Hans Moosmüller (hansm@dri.edu), J. Engelbrecht, R. K. Chakrabarty, and W. P. Arnott
Desert Research Institute, Nevada System of Higher Education, Reno, NV



MODIS images of smoke from Southern California wildfires (26-Oct.-2003)



Saharan Dust Plume (February 26, 2000)
(Courtesy SeaWiFS/Ocean Color Team)

What Determines the Temperature of the Earth?
0-dimensional Analysis: Štefan-Boltzmann Law

Energy Balance: $$(1-\alpha)S = 4\varepsilon\sigma T^4$$

Resulting Temperature $$T = \sqrt[4]{\frac{(1-\alpha)S}{4\varepsilon\sigma}} = 289\,K$$

σ **is the Stefan-Boltzmann constant**
S **is the Solar constant** (variable)
α **is the planetary albedo** (aerosols, clouds, surface)
ε **is the emissivity**
(greenhouse gases, clouds, surface)

Jožef Štefan 1835-1893

Ludwig Boltzmann 1844-1906

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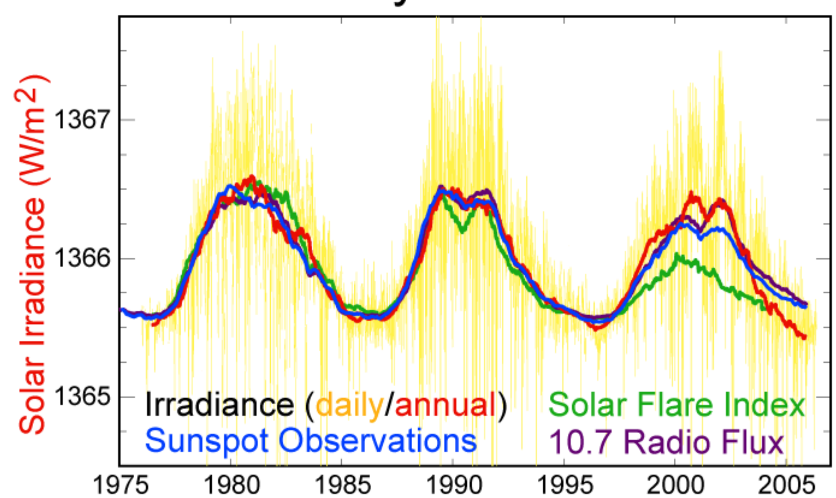
Solar Cycle Variations



Why Do We Care About Albedo (1)?

Scales:

1. Planetary (0-dimensional)

(SURFACE+CLOUDS+ATMOSPHERE)

The earth’s current planetary albedo is **0.29**.

A change of 0.01 corresponds to a change in global energy balance of 3.4 W/m^2 similar in impact to doubling the atmospheric CO_2 concentration.

The earth’s mean temperature is driven by its mean albedo and emissivity

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Wielicki, B. A., T. M. Wong, N. Loeb, P. Minnis, K. Priestley, and R. Kandel (2005). Changes in Earth's Albedo Measured by Satellite. *Science*, **308**, 825-825.
Ramanathan, V. (2008). Why is Earth's Albedo 29% and Was it Always 29%? *ILEAPS*, **5**, 18-20.

How Do We Determine the Earth's Albedo?

1. **Bean Counting**

   local measurements of surface albedo, cloud cover, aerosols, etc.

2. **Satellite Measurements**
3. **Earthshine**

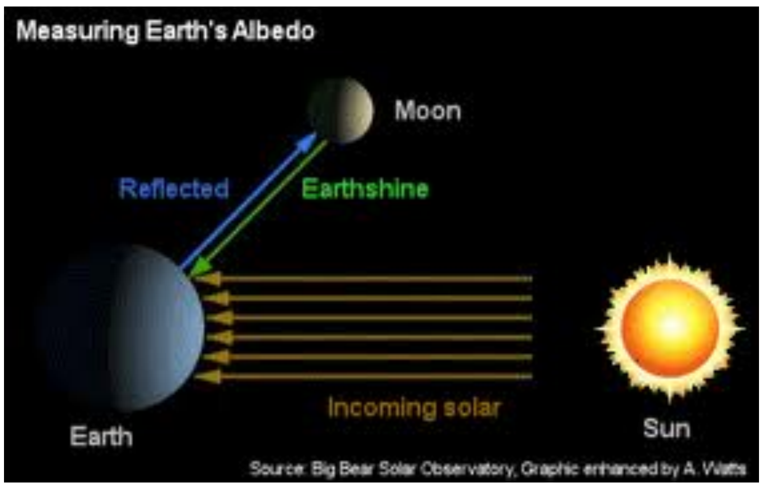

TABLE 2. Estimates of Planetary Albedo

Source	Albedo
Very [1912]	0.89
Russell [1916]	0.41–0.49
Dines [1917]	0.5
Aldrich [1922]	0.43
Earthshine ⇒ *Danjon* [1928]	0.29
Simpson [1928a, b]	0.43
Baur and Phillips [1934]	0.415
Fritz [1948]	0.347
Houghton [1954]	0.34
London [1957]	0.325
Satellite estimate [see *House et al.*, this issue]	0.3

Hunt, G. E., R. Kandel, and A. T. Mecherikunnel (1986). A History of Presatellite Investigations of the Earth's Radiation Budget. *Reviews of Geophysics*, **24**, 351-356.

House, F. B., A. Gruber, G. E. Hunt, and A. T. Mecherikunnel (1986). History of Satellite Missions and Measurements of the Earth Radiation Budget (1957-1984). *Reviews of Geophysics*, **24**, 357-377.

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Importance of Aerosol Albedo (SSA)

What do aerosols do?:

1. Aerosols contribute to **heating** if they are darker than the scene below
   Heating: **Single Scattering Albedo (SSA) < Surface Albedo**
2. Aerosols contribute to **cooling** if they are whiter than the scene below
   Cooling: **Single Scattering Albedo (SSA) < Surface Albedo**

$$SSA = \frac{\sigma_{sca}}{\sigma_{ext}} = \frac{\sigma_{sca}}{\sigma_{sca} + \sigma_{abs}}; \qquad 0 \le SSA \le 1$$

Reality is more complicated: Even a 1-d radiative transfer model needs to take the aerosol asymmetry parameter and multiple scattering/reflection into account.

$$\Delta F_R = \frac{S}{4} T_{atm}^2 (1-N)\tau\left[(1-a)^2(1-g)\omega - 4a(1-\omega)\right]$$

Low albedo (i.e., black) aerosols change planetary albedo while suspended and after deposition on high albedo snow and ice surface

Chýlek, P., and J. Wong (1995). Effect of Absorbing Aerosol on Global Radiation Budget. *Geophys. Res. Lett.*, **22**, 929-931.

Why Do We Care About Albedo (2)?

Scales:

2. Planetary (1-dimensional)

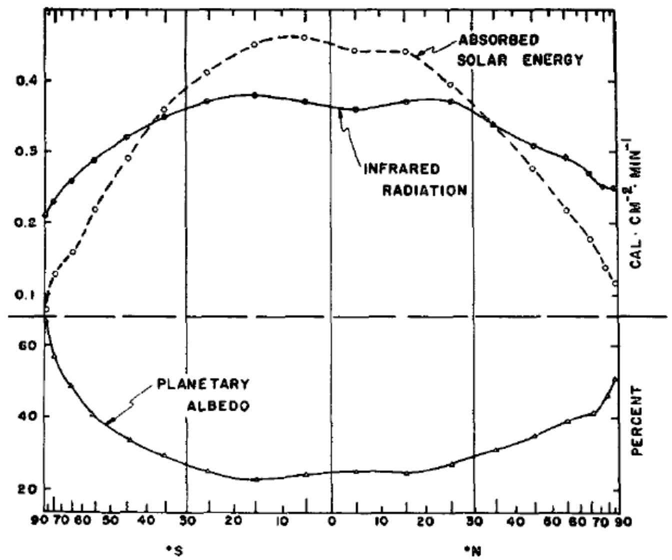

FIG. 1. Mean meridional profiles (averages within latitude zones) of components of the earth's radiation budget measured during the period 1962–66. The abscissa is scaled by the cosine of latitude.

$$RN = I_0(1 - A) - RL$$

RN = Net Radiation

I_0 = Incoming Solar Radiation

RL = Infrared Energy Loss to Space

This is the ultimate driving force for large-scale atmospheric and oceanic circulations (the earth as a heat engine)

Vonder Haar, T. H., and V. E. Suomi (1969). Satellite Observations of the Earth's Radiation Budget. *Science*, **163**, 667-668.

Vonder Haar, T. H., and V. E. Suomi (1971). Measurements of the Earth's Radiation Budget from Satellites during a Five-Year Period. Part I: Extended Time and Space Means. *J. Atmos. Sci.*, **28**, 305-314.

Lewis, J. M., D. W. Martin, R. M. Rabin, and H. Moosmüller (2010). Suomi: Pragmatic Visionary. *Bull. Amer. Meteor. Soc.*, **91**, 559-577.

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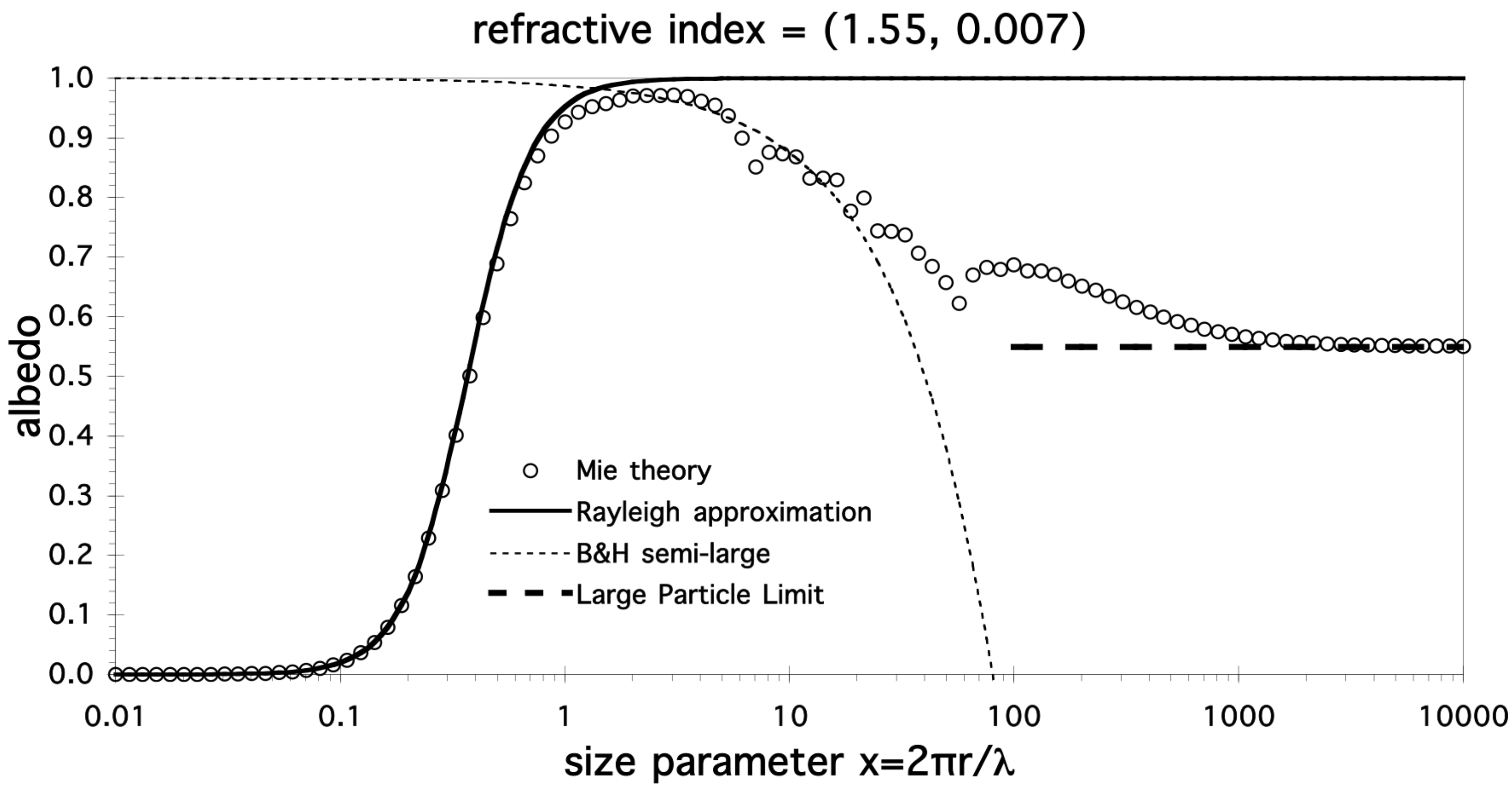
Aerosol Albedo (SSA)

Depends on Complex Refractive Index, Size, and Morphology



Moosmüller, H. and W. P. Arnott (2009). Particle Optics in the Rayleigh Regime. *J. Air & Waste Manage. Assoc.*, **59**, 1028-1031.

What Parameter Spectra Are Needed for Aerosol Radiative Transfer?

Absorption Coefficient:	How much light is absorbed? ⇒ Local heating of the atmosphere!
Scattering Coefficient:	How much light is scattered? ⇒ But where does it go?
Extinction Coefficient:	Scattering + Absorption Coefficient
Single Scattering Albedo:	Whiteness (Scattering/Extinction)
Phase Function:	Direction of the scattered light
Asymmetry Parameter:	Parameterization of Phase Function

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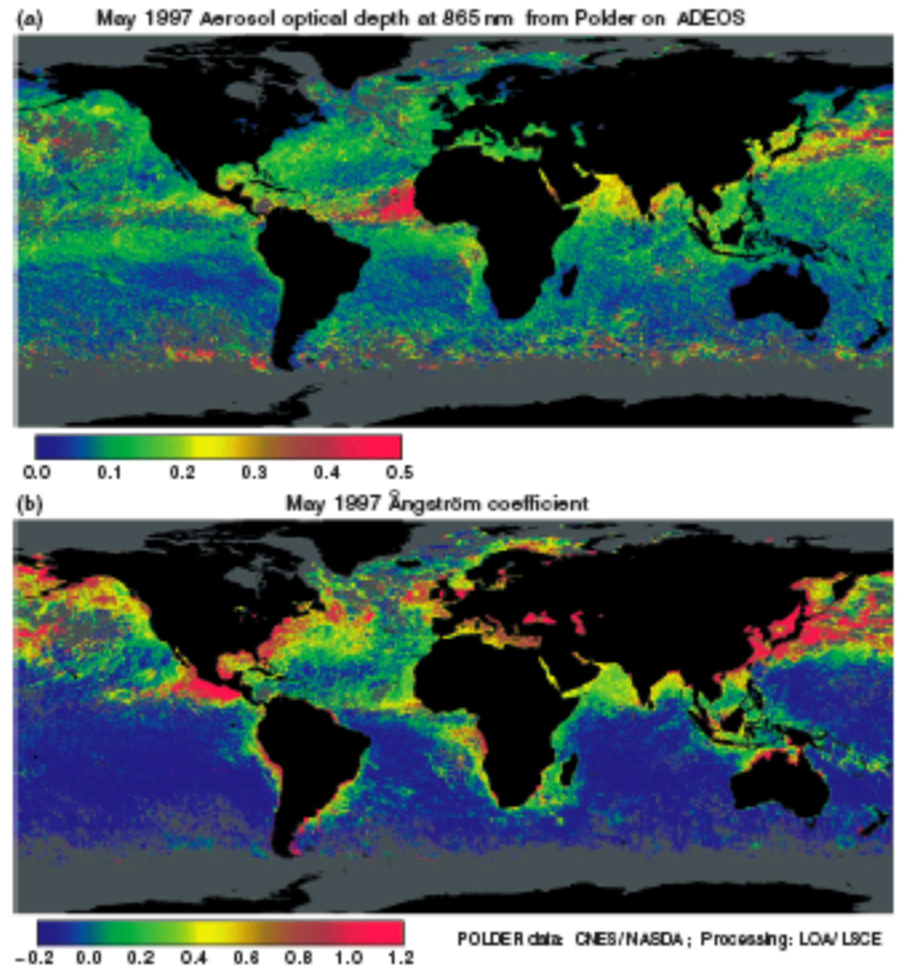
Where and When are These Parameters Needed?

Aerosols are distributed very inhomogeneously in space and time

<u>Ultimate Goal:</u>
24/7 Global Coverage Desired

<u>Our Initial Goal:</u>
Local Measurements



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Remote Sensing of Aerosol Optical Properties

Extinction and directional scattering are relatively easy.☺

Absorption, Integrated Scattering, Phase Function, and Single Scattering Albedo are difficult and need multi-angle measurements. ☹

1. Column Integrated: Transmissometer, Sunphotometers (e.g., AERONET), Satellite (e.g., MODIS, MISR, GLORY^{RIP})
2. Spatially Resolved: Mono-Static and Bi-Static Lidar (Lidar Ratio is generally unknown => HSRL)

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Moosmüller, H., R. K. Chakrabarty, and W. P. Arnott (2009). Aerosol Light Absorption and its Measurement: A Review. *J. Quant. Spectrosc. Radiat. Transfer.*, **110**, 844-878.

In Situ Measurements of Aerosol Optical Properties

1. Measure Absorption and Scattering or Extinction Coefficients (for large SSA).
2. We Use Photoacoustic Instrument for Measurement of Absorption Coefficient at Multiple Wavelengths.
3. This Instrument Has an Integrated Reciprocal Nephelometer to Measure Scattering Coefficient Simultaneously in the Same Sample Volume, at the Same Wavelengths.
4. Also Yields SSA and Extinction Coefficient.

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Moosmüller, H., R. K. Chakrabarty, and W. P. Arnott (2009). Aerosol Light Absorption and its Measurement: A Review. *J. Quant. Spectrosc. Radiat. Transfer.*, **110**, 844-878.

Photoacoustic Instrument

1. Based on and calibrated with first principles.
2. High time resolution (up to 1 s).
3. Large (10^6) dynamic range (ambient to sources).
4. Good sensitivity ($\approx 0.5\ Mm^{-1} \cong 50\ ng/m^3$ of BC).
5. Compact (19” rack mount) and rugged (airborne operation).
6. Commercially available

Arnott, W. P., H. Moosmüller, C. F. Rogers, T. Jin, and R. Bruch (1999). “Photoacoustic Spectrometer for Measuring Light Absorption by Aerosol: Instrument Description.” *Atmos. Environ.* **33**, 2845-2852.

Arnott, W. P., H. Moosmüller, and J. W. Walker (2000). “Nitrogen Dioxide and Kerosene-Flame Soot Calibration of Photoacoustic Instruments for Measurement of Light Absorption by Aerosols.” *Rev. Sci. Instrum.* **71**, 4545-4552.

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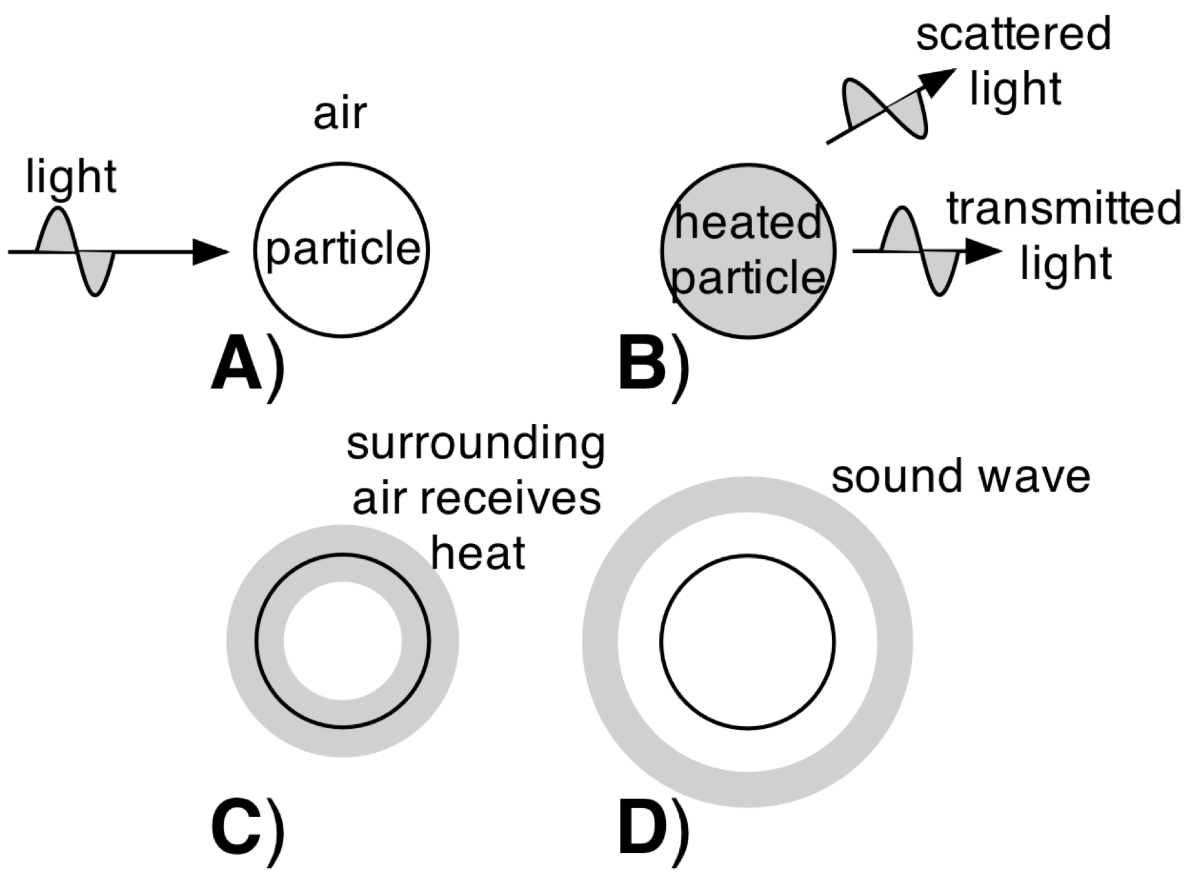
Photoacoustic Effect



A) Light is incident on a particle. B) Some of the incident light is absorbed by the particle, some is transmitted, and some is scattered. The particle is heated by light absorption. C) Heat transfers from the particle to the surrounding air. D) The surrounding air expands upon receiving heat, resulting in an outgoing acoustic wave.

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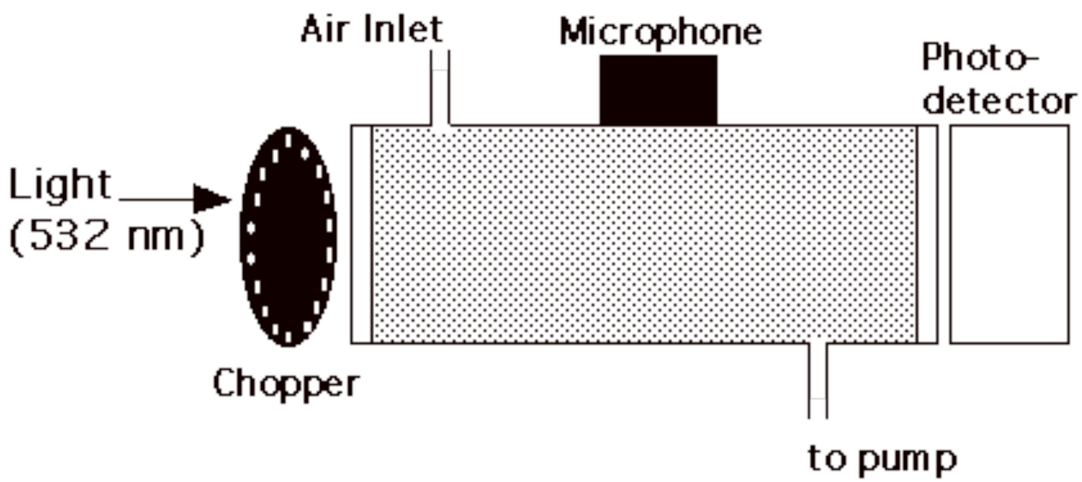
Photoacoustic Instrument

•Laser light is power modulated by the chopper.

•Light absorbing aerosols convert light to heat - a sound wave is produced.

•Microphone signal is a measure of the light absorption.

•Light scattering aerosols don't generate heat.



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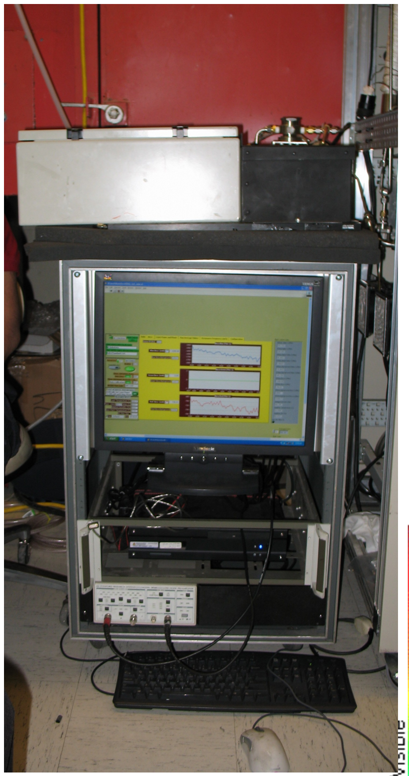
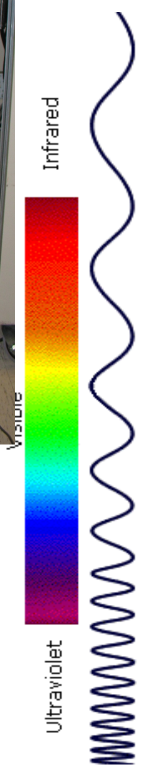
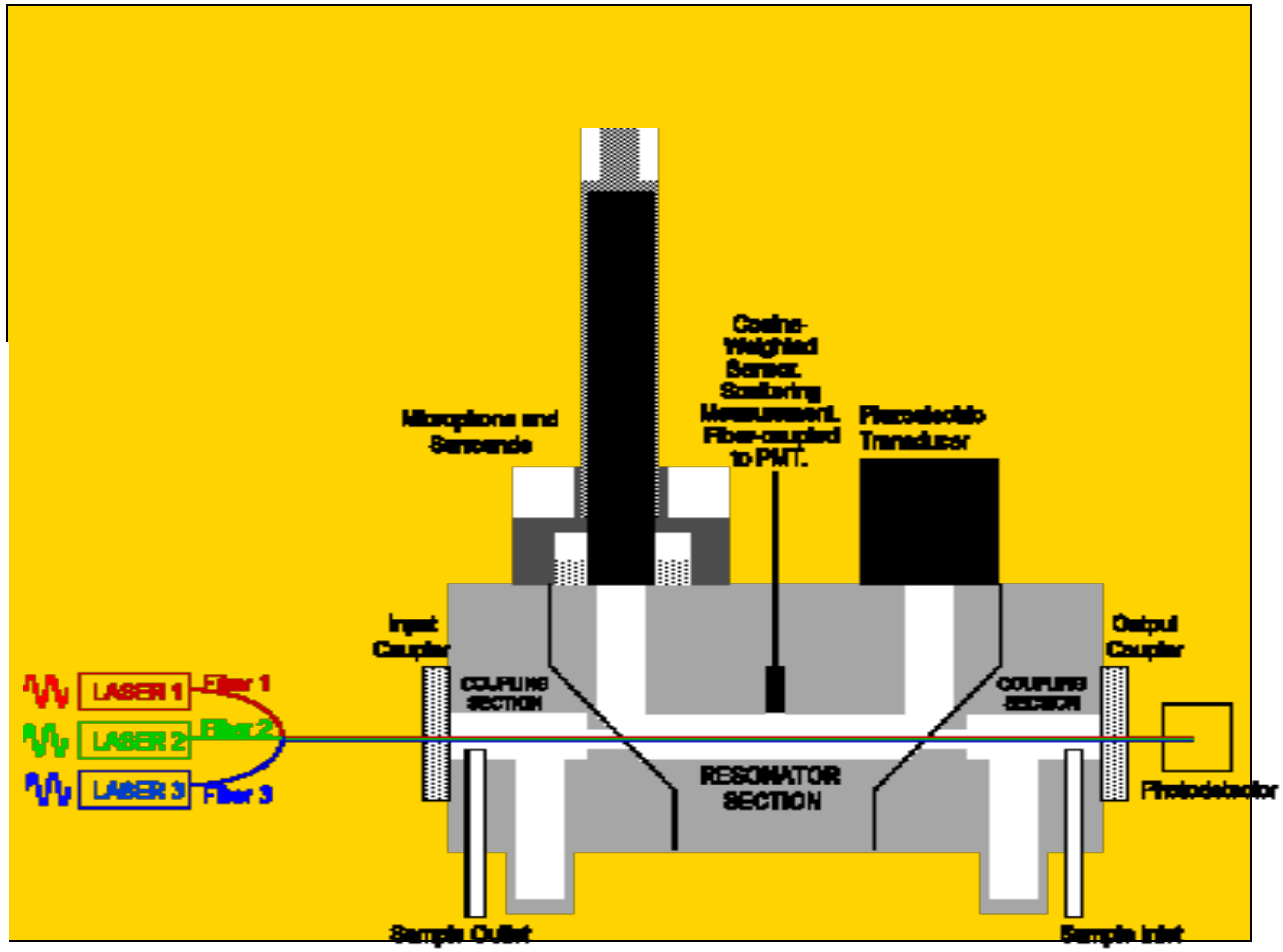
Three Wavelength Photoacoustic (Absorption)

Instrument with Nephelometer (Scattering) Sensor







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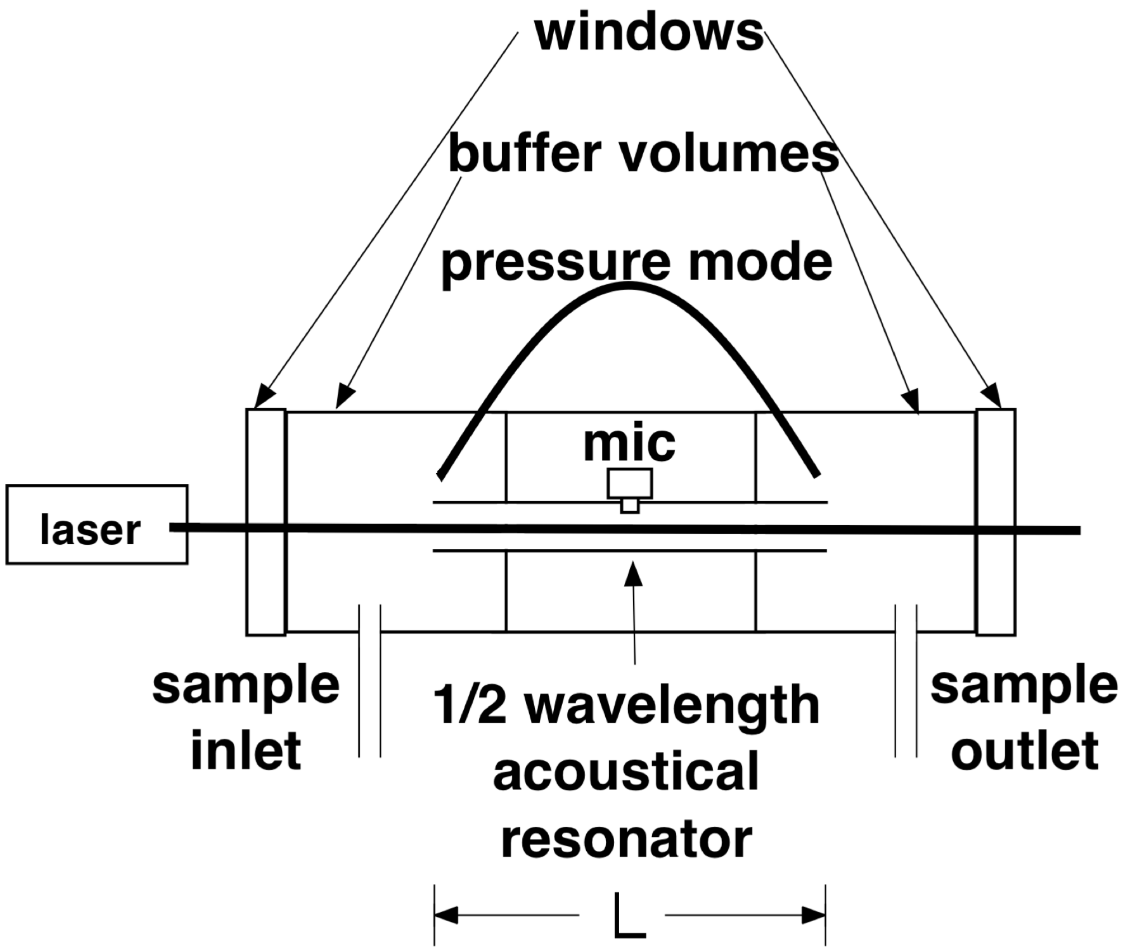
"Mini" Photoacoustic Instrument



Schematic of a ½ wavelength longitudinal photoacoustic instrument with pressure nodes at the ends of the ½ wavelength resonator, and a pressure antinode at the microphone position. Buffer volumes act as pressure release boundary conditions for the resonator, and they facilitate sample and laser beam passage through the resonator. The diameter of the acoustical resonator is as small as possible to maximize the microphone signal.

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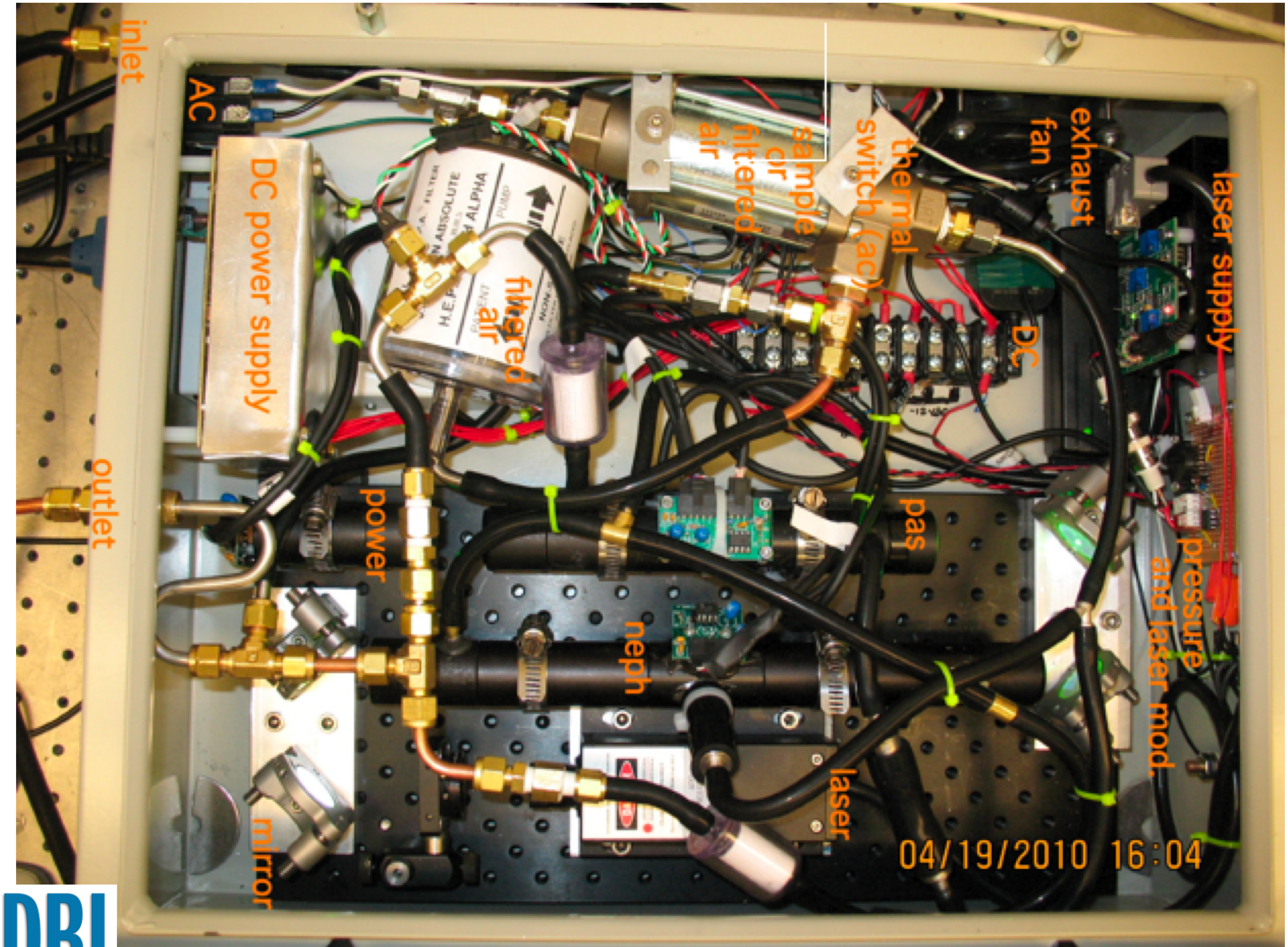
“Mini” Photoacoustic Instrument



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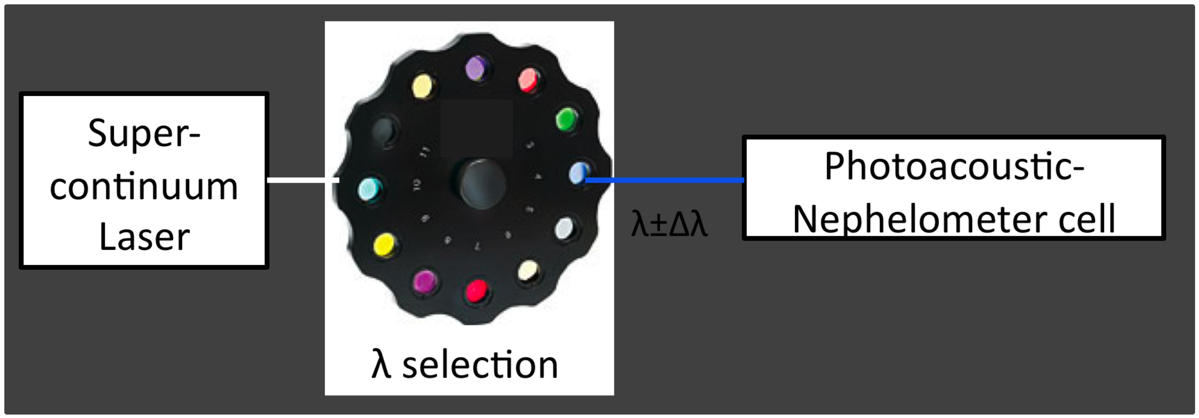
Emerging New Technology for

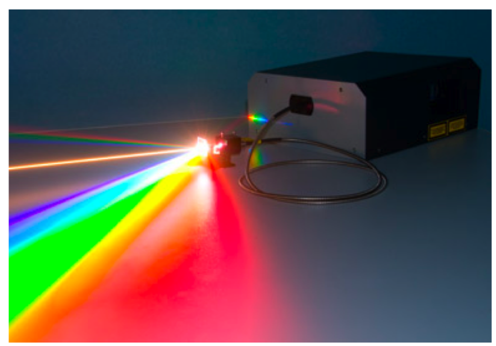
Broadband Photoacoustic and Nephelometry Spectroscopy

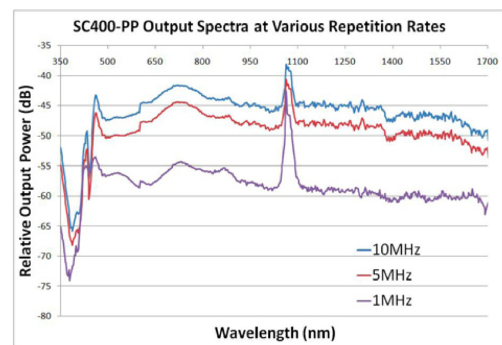
Claudio Mazzoleni, Hans Moosmüller and Pat Arnott



- Laser bandwidth: 400- 2200 nm
- Spectral power density ~2mW/nm
- Single channel bandwidth ~ 40nm with ~80mW
- Targeted detection limit ~ 3Mm^{-1}/sec

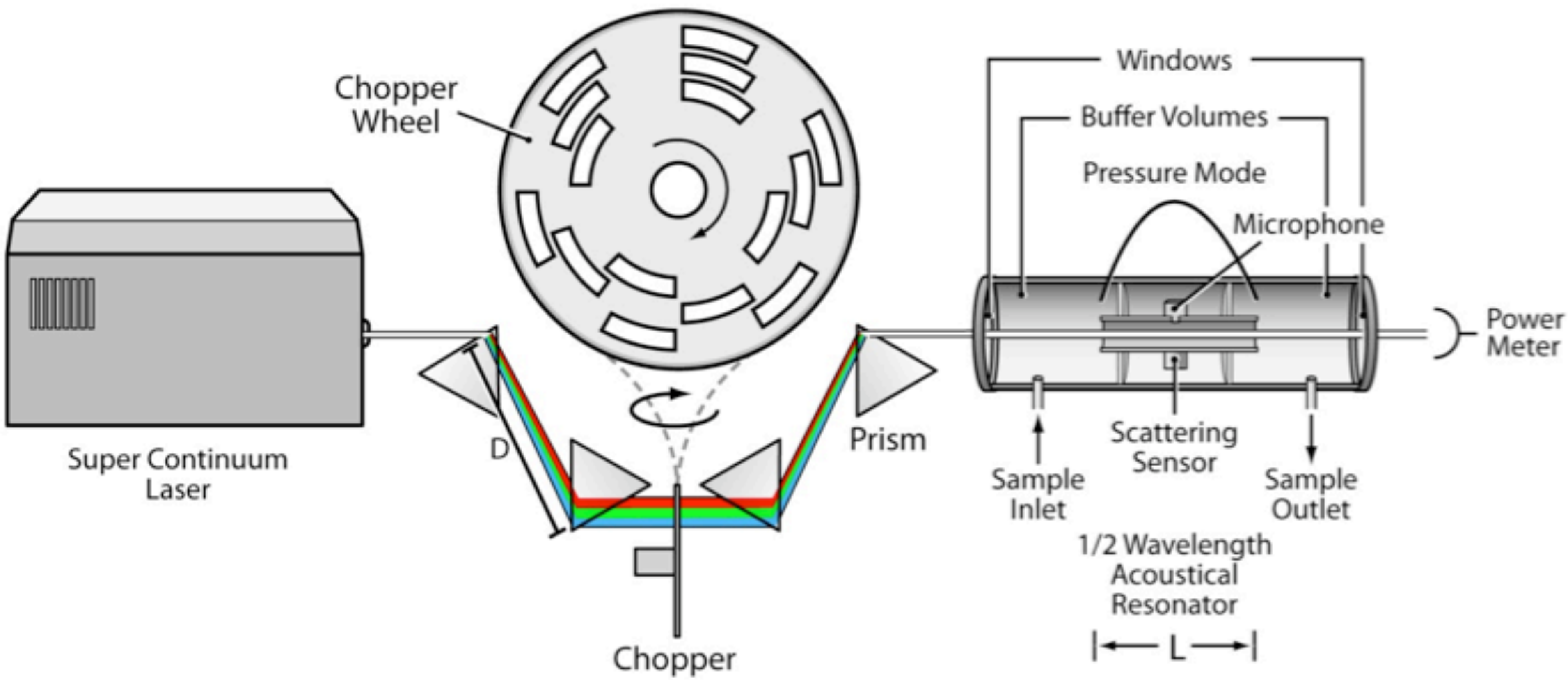
A prototype of the instrument in the Lab





Fianium Pico-second Super-continuum Laser (400-2200 nm)

Photoacoustic Aerosol Light Absorption and Albedo Spectrometer (PALAAS)



Schematic setup of PALAAS showing the light source, wavelength encoder consisting of a four prism pulse compressor, a custom chopper (simplified here for only three wavelength bands and low modulation frequencies), and the acoustical resonator followed by a power meter for the measurement of laser power.

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Recent Developments Regarding Photoacoustic Instruments at UNR/DRI

1. Instrument Commercialized
2. Integrated Scattering Sensor for Albedo (SSA)
3. Multiple Wavelengths in the Same Instrument
4. Miniature Instrument Developed & Commercialized
5. Calibration with Oxygen A-Band (help from NIST)
6. UV wavelength added

Current Development: Measurements at many (e.g., 32) wavelengths covering most of the solar spectrum (i.e., 400-2300 nm): NSF MRI

Abu-Rahmah, A., W. P. Arnott, and H. Moosmüller (2006). Integrating Nephelometer with a Low Truncation Angle and an Extended Calibration Scheme. *Meas. Sci. Tech.*, **17**, 1723-1732.

Lewis, K., W. P. Arnott, H. Moosmüller, and C. E. Wold (2008). Strong Spectral Variation of Biomass Smoke Light Absorption and Single Scattering Albedo Observed with a Novel Dual-Wavelength Photoacoustic Instruments. *J. Geophys. Res.*, **113**, doi: 10.1029/2007JD009699.

Tian, G., H. Moosmüller, and W. P. Arnott (2009). Simultaneous Photoacoustic Spectroscopy of Aerosol and Oxygen A-band Absorption for the Calibration of Aerosol Light Absorption Measurements. *Aerosol Sci. Tech.*, **43**, 1084-1090.

Gillis, K. A., D. K. Havey, and J. T. Hodges (2010). Standard Photoacoustic Spectrometer: Model and Validation Using O_2 A-band spectra. *Rev. Sci. Instrum.*, **81**, 064902.

Gyawali, M., W. P. Arnott, R. Zaveri, C. Song, H. Moosmüller, L. Liu, and M. I. Mishchenko (2011). Photoacoustic Aerosol Optics Measurements at UV, VIS, and Near IR Wavelengths for Laboratory Generated Aerosols and Ambient Urban Aerosols during Polluted and Clean Days. *Atm. Chem. Phys.*, in preparation.

What Are We Doing with These Photoacoustic Instruments

Aerosols of atmospheric importance with poorly characterized spectra of absorption and scattering coefficients are:

1. **Carbonaceous Aerosols**
   (especially from smoldering biomass burning)
2. **Mineral Dust Aerosols**

GOAL: Characterize absorption and scattering coefficient spectra of these aerosols in the laboratory and in ambient environments for improvements of radiative transfer calculations and remote sensing measurements (e.g., satellite and AERONET)

Biomass Burning Aerosol Emissions

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McMeeking, G. R., S. M. Kreidenweis, S. Baker, C. M. Carrico, J. C. Chow, J. L. Collett Jr., W. M. Hao, A. S. Holden, T. W. Kirchstetter, W. C. Malm, H. Moosmüller , A. P. Sullivan, and C. Wold (2009). Emissions of Trace Gases and Aerosols during the Open Combustion of Biomass in the Laboratory. *J. Geophys. Res.*, **114**, doi:10.1029/2009JD011836.

Aerosols from Biomass Burning

Incomplete Combustion of mostly $\mathbf{C_6H_9O_4}$

Emissions of gases and **Carbonaceous Particles**

Carbonaceous Particles consist mostly of Black Carbon (**BC**) and Organic Carbon (**OC**)

Black Carbon (**BC**) is Black (Strong Absorption)

Organic Carbon (**OC**) is:

1) **Classical View: No strong light absorption**
2) **New Results: Contains Brown Carbon (BrC) with strong light absorption in the blue & UV**

Bond, T. and R. Bergstrom (2006). "Light Absorption by Carbonaceous Particles: An Investigative Review." *Aerosol Sci. Tech.* **40**, 1-41.

Kirchstetter, T. W., T. Novakov, and P. V. Hobbs (2004). Evidence that the Spectral Dependence of Light Absorption by Aerosols is Affected by Organic Carbon. *J. Geophys. Res.*, **109**, DOI:10.1029/2004JD004999.

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Global Emissions of BC/OC Aerosols

Table 1. Previous Estimates of BC and OC Emissions From Combustion[a]

Reference	Year[b]	Fossil Fuel		Biofuel/Biomass		Combined	
		BC	OC	BC	OC	BC	OC
Turco et al. [1983]	?	1.3–8.3	–	1.3–14	–	2.6–22	–
Penner et al. [1993]							
Based on fuel consumption	1980[c]	6.6	–	6.0	–	13	–
Based on ratios with sulfur	–	–	–	–	–	24	–
Cooke and Wilson [1996]	1984	8.0	–	6.0	–	14[d]	–
Liousse et al. [1996]	–	6.6[e]	28	5.6	45	12	73
Cooke et al. [1999]							
<1 μm	1984	5.1	10	–	–	–	–
"Bulk" (all sizes)	1984	6.4	7.0	–	–	–	–
Andreae and Merlet [2001][f]	–	–	–	4.8	36	–	–
This work	1996	3.0	2.4	5.0	31	8.0	33

[a]Units are Tg/yr.
[b]Year is that of energy consumption data.
[c]Other years appear to be included for some locations and fuels.
[d]Excludes biofuels.
[e]From *Penner et al.* [1993].
[f]The literature contains several estimates of emissions from biomass burning. As this document focuses on revision of fossil and biofuel emission factors, we summarize only the latest open-biomass estimate here.

87% of carbonaceous aerosol mass emissions are from biomass burning
86% of that mass are OC emissions from smoldering combustion

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Bond, T. C., D. G. Streets, et al. (2004). "A Technology-Based Global Inventory of Black and Organic Carbon Emissions from Combustion." Journal of Geophysical Research **109** (D14203): DOI:10.1029/2003JD003697.

Absorption Ångström Coefficient (*AAC*)

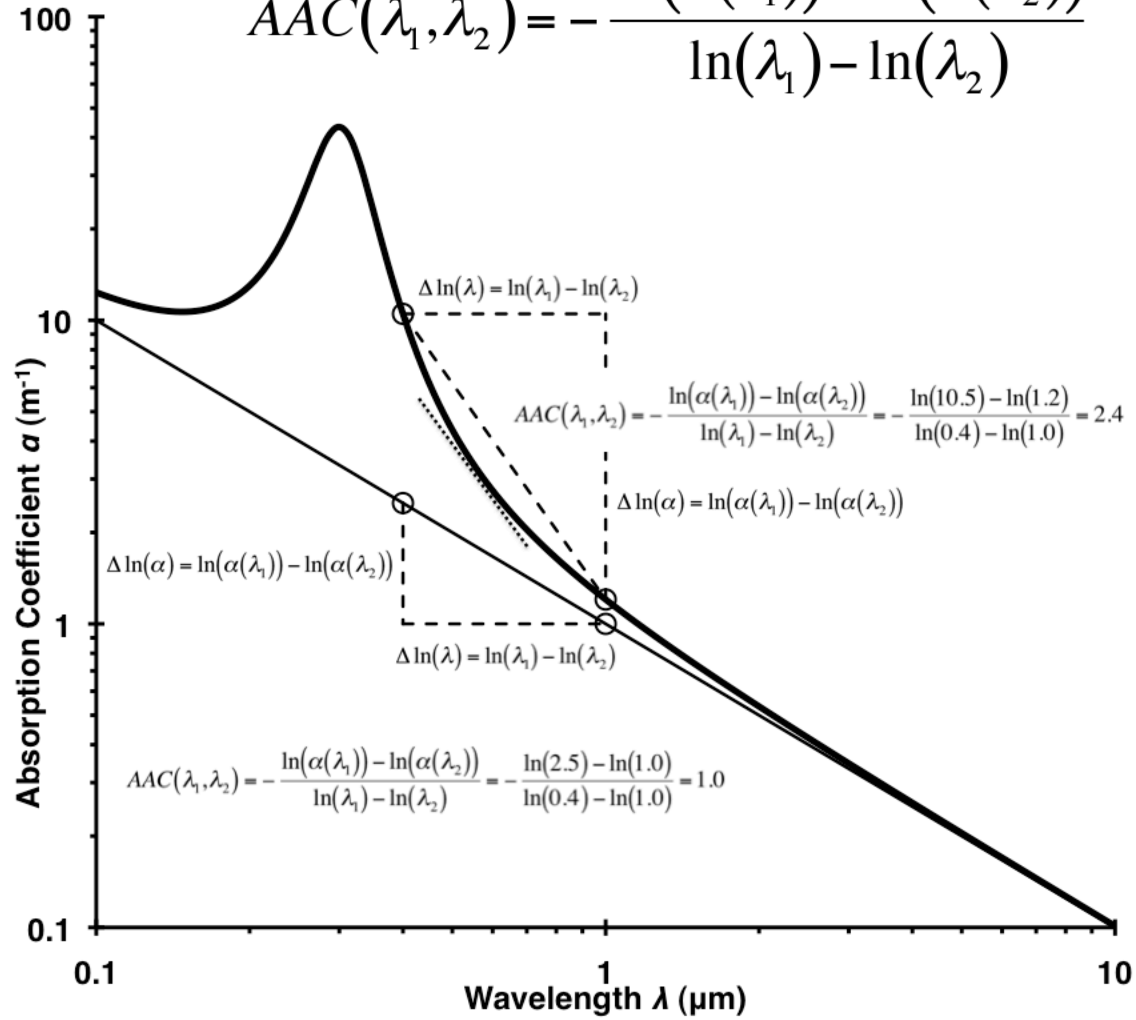
$$AAC(\lambda_1,\lambda_2) = -\frac{\ln(\alpha(\lambda_1)) - \ln(\alpha(\lambda_2))}{\ln(\lambda_1) - \ln(\lambda_2)}$$

Definition:

$$\frac{\alpha(\lambda_1)}{\alpha(\lambda_2)} = \left(\frac{\lambda_1}{\lambda_2}\right)^{-AAC}$$

***AAC* is the negative slope of the absorption coefficient as a function of wavelength in a log-log plot**

Importance: Extrapolating absorption from one wavelength (e.g., OMI) to another one (e.g., MODIS or Calipso)



Moosmüller, H., R. K. Chakrabarty, K. M. Ehlers, and W. P. Arnott (2011). Absorption Ångström Coefficient, Brown Carbon, and Aerosols: Basic Concepts, Bulk Matter, and Spherical Particles. *Atm. Chem. Phys.,* **11**, 1217-1225.

Simple Analytical Relationships between Ångström Coefficients of Aerosol Extinction (*EAC*), Scattering (*SAC*), Absorption (*AAC*), and Single Scattering Albedo (*SSAAC*)

$$EAC(\lambda) = \left[1 - \omega(\lambda)\right] AAC(\lambda) + \omega(\lambda) SAC(\lambda)$$

$$SSAAC(\lambda) = \left[1 - \omega(\lambda)\right] \left(SAC(\lambda) - AAC(\lambda)\right)$$

$$SSAAC(\lambda) = SAC(\lambda) - EAC(\lambda)$$

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Moosmüller, H. and R. K. Chakrabarty (2011). Technical Note: Simple Analytical Relationships between Ångström Coefficients of Aerosol Extinction, Scattering, Absorption, and Single Scattering Albedo. *Atm. Chem. Phys. Discuss.* **11**, 19213-1922.

Black Carbon (BC)

Wavelength independent imaginary part of the refractive index ⇒ for small particles:

Absorption coefficient ~ 1/wavelength

Absorption Ångström Coefficient (*AAC*) = 1

<u>BC is related to:</u>

1. Elemental carbon (EC): Thermally refractory; thermal-optical method
2. Graphitic Carbon (GC): Graphitic lattice structure; Raman spectroscopy or x-ray diffraction
3. Insoluble Carbon (IC): Insoluble in polar and non-polar solvents

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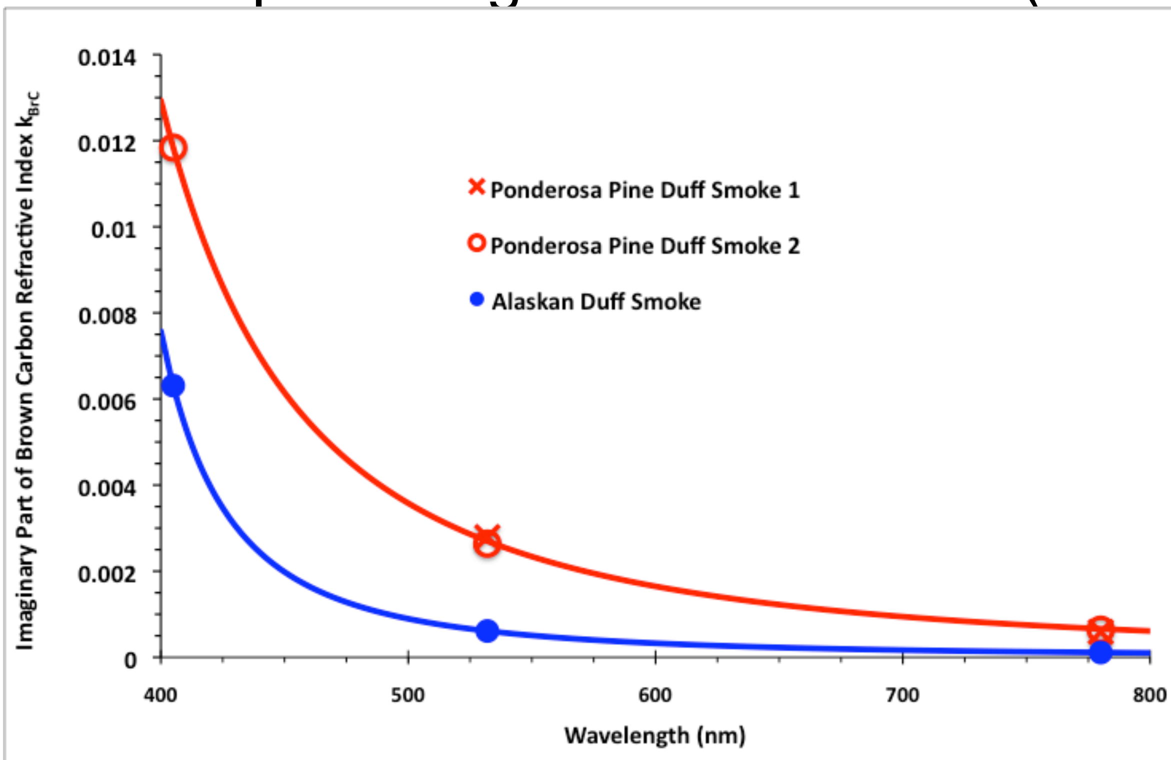
Moosmüller, H., R. K. Chakrabarty, and W. P. Arnott (2009). Aerosol Light Absorption and its Measurement: A Review. *J. Quant. Spectrosc. Radiat. Transfer*.

Brown Carbon (BrC)

Wavelength dependent imaginary part of the refractive index increases towards shorter wavelengths

⇒ Absorption coefficient ~ 1/(wavelength)^{AAC}

Bulk Absorption Ångström Coefficient (AAC) >> 1



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Chakrabarty, R. K., H. Moosmüller, L.-W. A. Chen, K. Lewis, W. P. Arnott, C. Mazzoleni, M. Dubey, C. E. Wold, W. M. Hao, and S. M. Kreidenweis (2010). Brown Carbon in Tar Balls from Smoldering Biomass Combustion. *Atm. Chem. Phys.,* **10**, 6363-6370. .

Absorption Ångström Coefficient (*AAC*)

AAC for bulk, small particles. or large particles?

Bulk:

$$\alpha_{bulk} = 4\pi \frac{k}{\lambda}$$

Small Particles: $\alpha_{small} \propto \alpha_{bulk} \xi(\lambda)$

ξ within 15% from one

Larger Particles: Complicated, need to do optical calculations (Mie, T-matrix, etc.)

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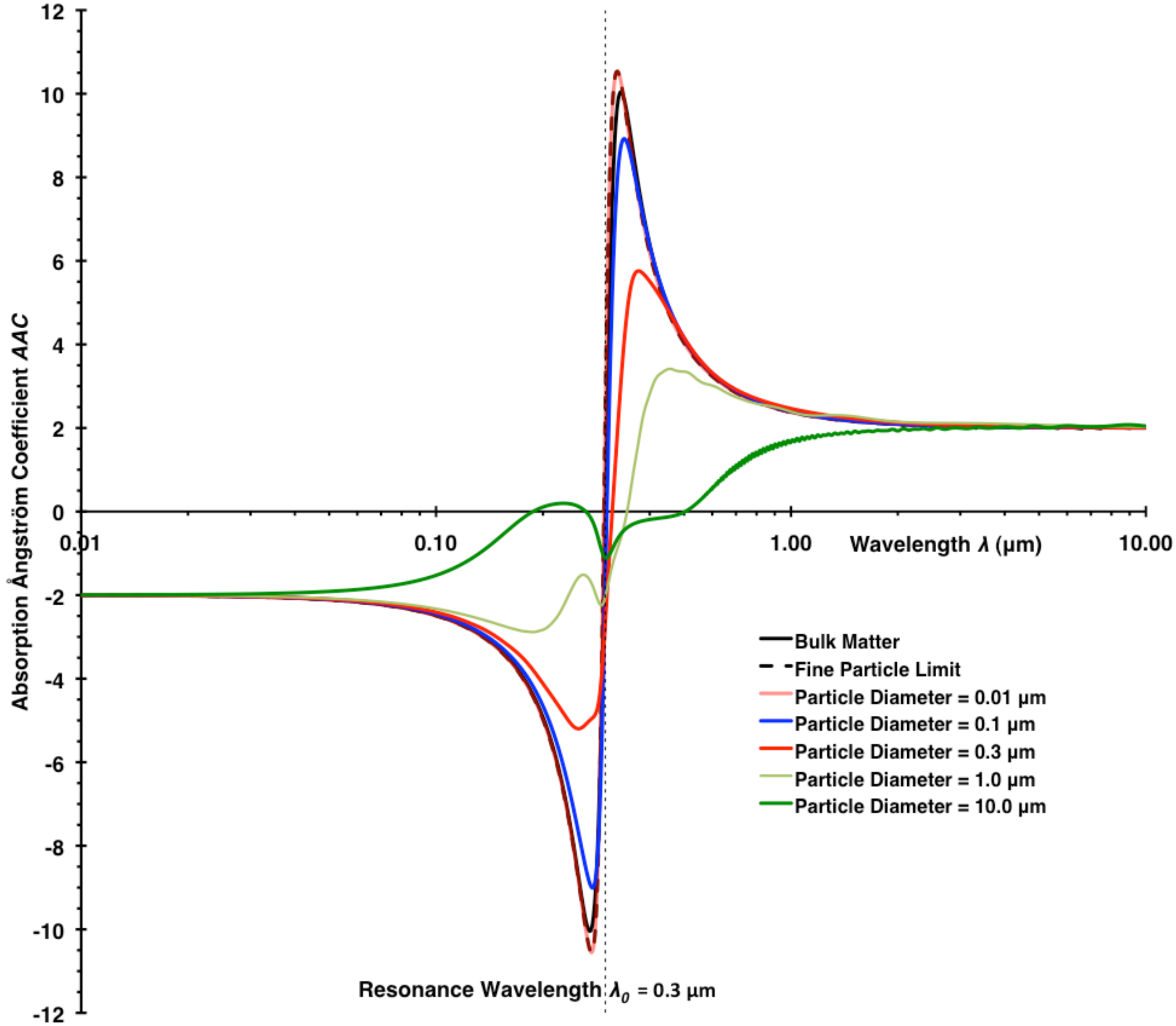
Sun, H. L., L. Biedermann, and T. C. Bond (2007). Color of Brown Carbon: A Model for Ultraviolet and Visible Light Absorption by Organic Carbon Aerosol. *Geophys. Res. Lett.*, **34**, doi:10.1029/2007GL029797.

Absorption Ångström Coefficient (*AAC*)



Bulk or Particles?

Moosmüller, H., R. K. Chakrabarty, K. M. Ehlers, and W. P. Arnott (2011). Absorption Ångström Coefficient, Brown Carbon, and Aerosols: Basic Concepts, Bulk Matter, and Spherical Particles. *Atm. Chem. Phys.,* **11**, 1217-1225.

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Brown Carbon (BrC; Optically Defined)

1. BrC is part of Organic Carbon (OC).
2. Chemical compounds constituting BrC are largely unidentified (connection to HULIS, watersoluble?).
3. Little is know about sources: biomass burning, especially smoldering combustion, secondary organic aerosol formation (primary and secondary?).
4. Little is known about sinks (dry and/or wet deposition?)
5. Little is known about atmospheric lifetimes

Chakrabarty, R. K., H. Moosmüller, L.-W. A. Chen, K. Lewis, W. P. Arnott, C. Mazzoleni, M. Dubey, C. E. Wold, W. M. Hao, and S. M. Kreidenweis (2010). Brown Carbon in Tar Balls from Smoldering Biomass Combustion. *Atm. Chem. Phys.,* **10**, 6363-6370. .

Moosmüller, H., R. K. Chakrabarty, and W. P. Arnott (2009). Aerosol Light Absorption and its Measurement: A Review. *J. Quant. Spectrosc. Radiat. Transfer*, **110**, 844-878.

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Biomass Burning

Aerosols from Solid Fuel Combustion: Flaming Followed by Smoldering Combustion

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Moosmüller, H., S. M. Kreidenweis, J. L. Collett Jr., W. M. Hao, and W. C. Malm (2007). Characterization of Particle Emissions from Laboratory Combustion of Wildland Fuels. Newsletter of the Integrated Land Ecosystem – Atmosphere Processes Study (iLEAPS), **4**, 22-23.

Flaming Followed by Smoldering Combustion

Flaming	**Smoldering**
High Combustion Efficiency (CO_2/TotC)	Low Combustion Efficiency (CO_2/TotC)
High Temperature	Low Temperature
Gaseous Diffusion Flame: Burns Volatiles	Surface Reaction: Burns Solids/Liquids
Dry, Fine Fuels	Wet, Large Fuels
Black Smoke (BC)	White Smoke (OC, BrC)
Low CO Emissions	High CO Emissions
Minutes to Hours	Minutes to Months

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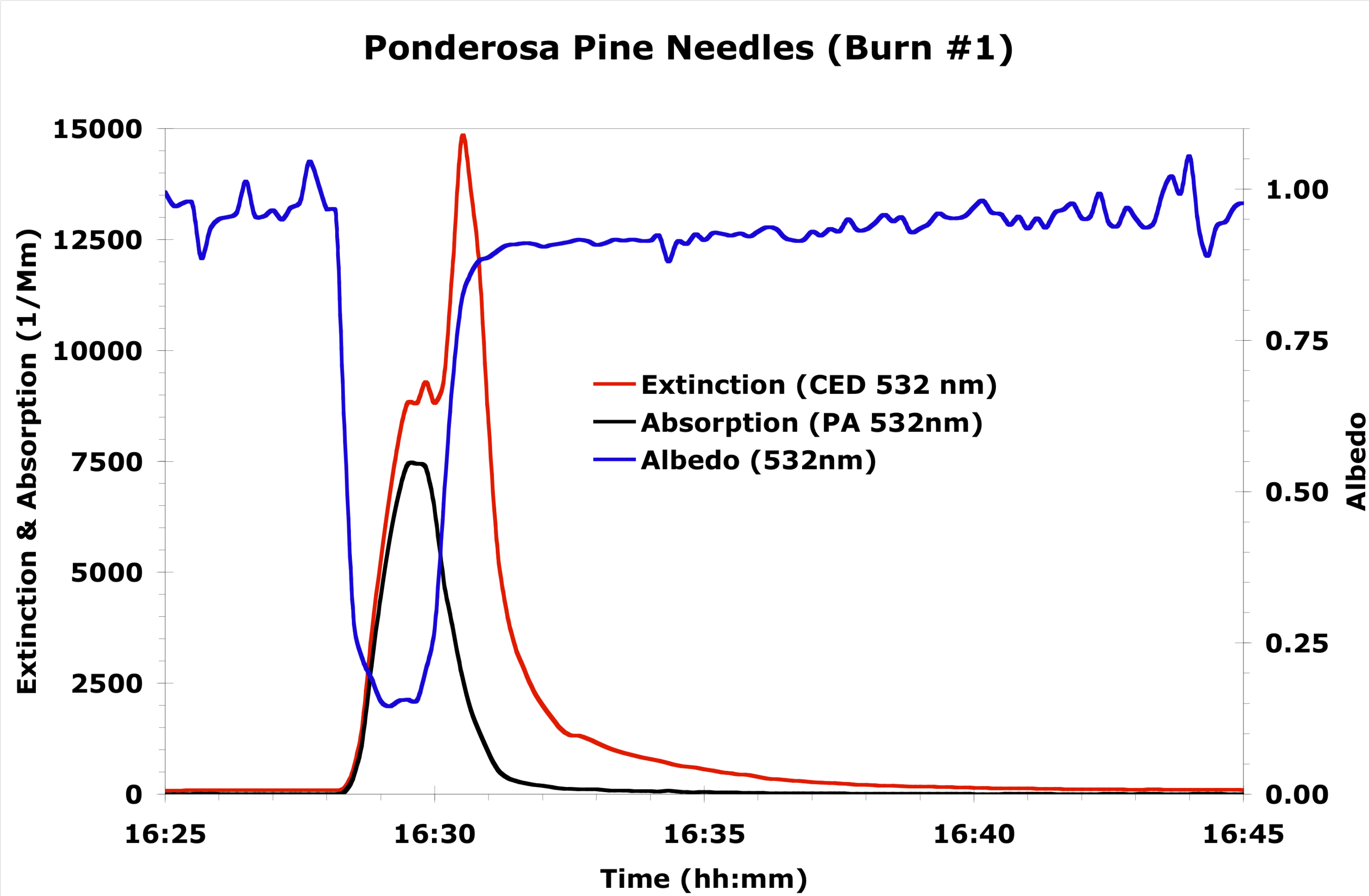
Time-Resolved Optical Properties



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Chen, L.-W. A., H. Moosmüller, W. P. Arnott, J. C. Chow, J. G. Watson, R. A. Susott, R. E. Babbitt, C. E. Wold, E. N. Lincoln, and W. M. Hao (2006). "Particle Emissions from Laboratory Combustion of Wildland Fuels: In Situ Optical and Mass Measurements." *Geophys. Res. Lett.* **33**, doi:10.1029/2005GL024838.

Albedo in Wildfires

Low Albedo (similar to oil fire)

High Albedo

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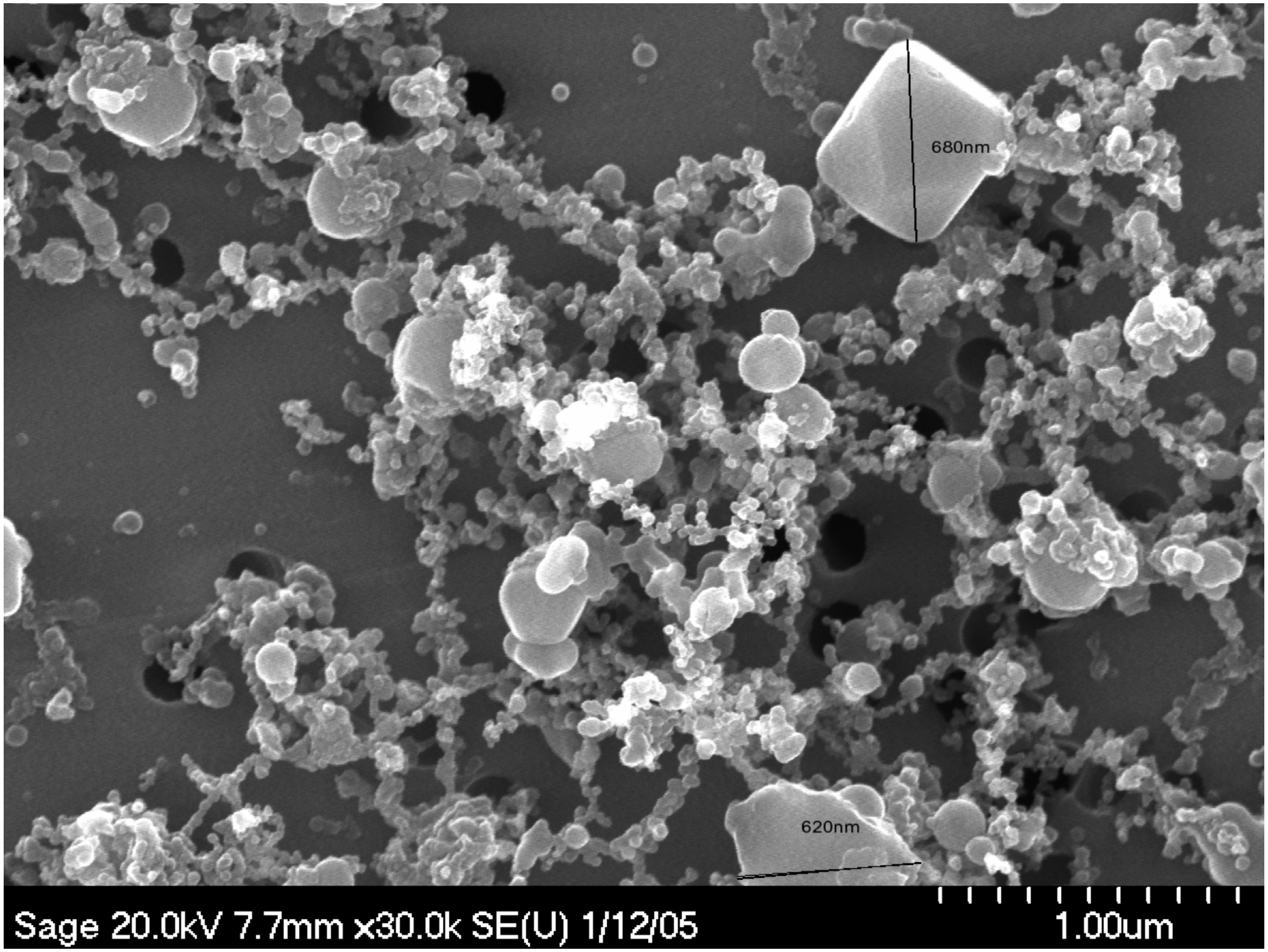
Waterfall Fire (Near Carson City, NV; 14-July-2004)

Structural Properties of Particles from Biomass Combustion



Large irregular shaped particles (KCl), tar balls, and fractal-like chain aggregates (soot) from the combustion of sagebrush

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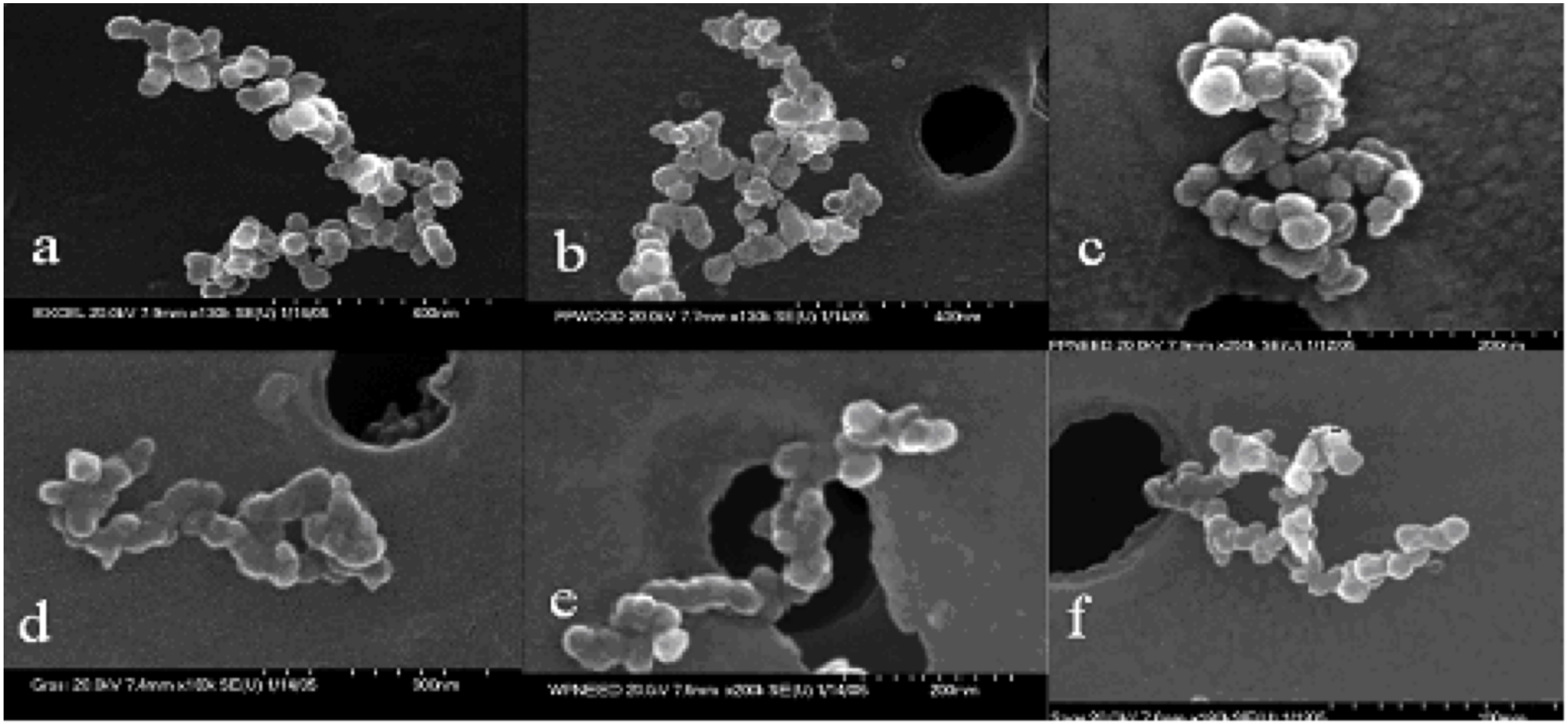
Chakrabarty, R. K., H. Moosmüller, M. A. Garro, W. P. Arnott, J. W. Walker, R. A. Susott, R. E. Babbitt, C. E. Wold, E. N. Lincoln, and W. M. Hao (2006). "Emissions from the Laboratory Combustion of Wildland Fuels: Particle Morphology and Size." *J. Geophys. Res.* **111**, doi:10.1029/2005JD006659.

Particles from Flaming Combustion

Fractal-like chain aggregates of EC monomers (30-50 nm) coated with OC



Soot particles from the flaming combustion of a) poplar wood, b) ponderosa pine wood, c) ponderosa pine needles, d) dambo grass, e) white pine needles, and f) sagebrush.

$$N = k_g \left(\frac{2R_g}{d_p} \right)^{D_f}$$

Fractal Dimension $D_f = 1.8$

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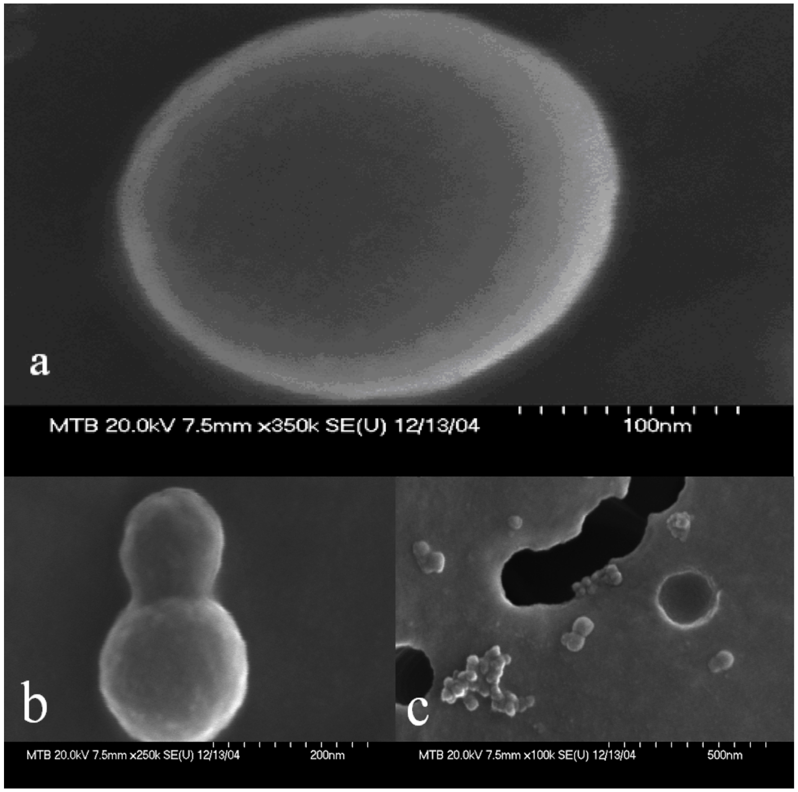
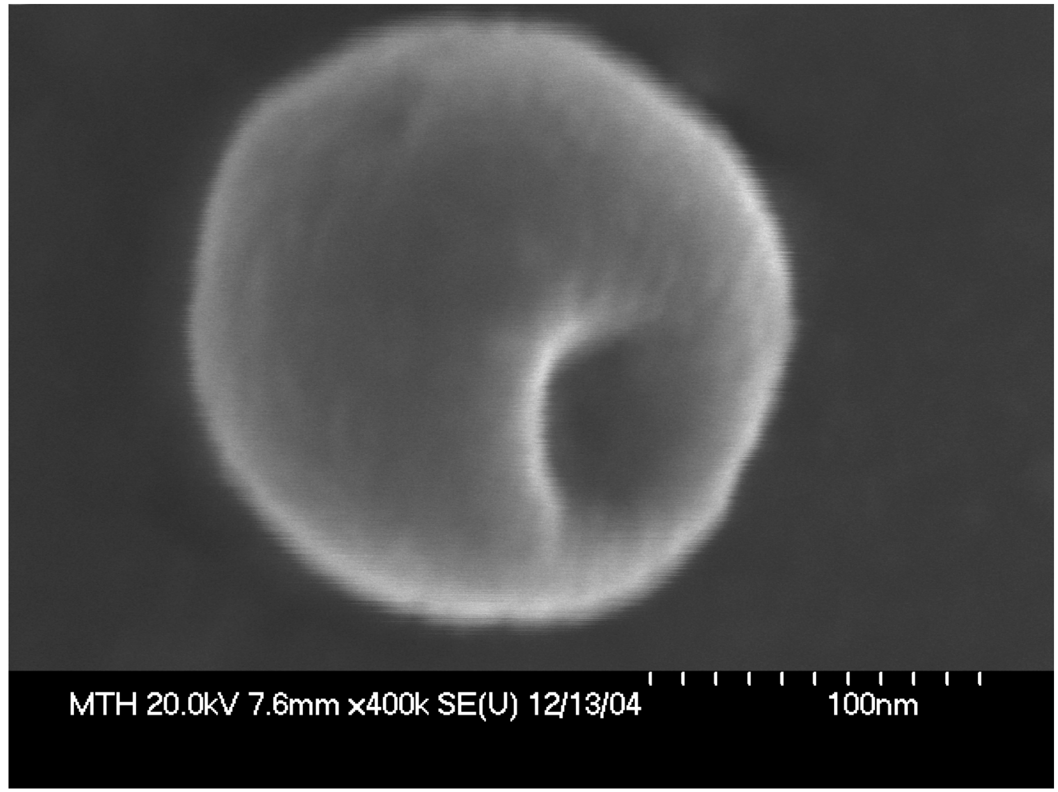
Particles from Smoldering Combustion

Near-spherical OC particles (bimodal 130 & 500nm)



Tar balls from the flaming combustion of Montana grass and tundra cores. These tar balls occur as individual spherical particles (a) as well as in small (b) and large (c) clusters.



Particle from the combustion of Montana grass showing structural defects sometimes found in spherical tar balls originating from the combustion of wet fuels

Chakrabarty, R. K., H. Moosmüller, M. A. Garro, W. P. Arnott, J. W. Walker, R. A. Susott, R. E. Babbitt, C. E. Wold, E. N. Lincoln, and W. M. Hao (2006). "Emissions from the Laboratory Combustion of Wildland Fuels: Particle Morphology and Size." *J. Geophys. Res.* **111**, doi:10.1029/2005JD006659.

Current and Future Work

1. Develop a biomass burning facility at DRI, Reno, NV (nearly completed).
2. Use this facility for additional laboratory work.
3. Quantify influence of morphology on radiative forcing (manuscript in preparation).
4. Identify chemical composition (functional groups?) of brown carbon.
5. Characterize absorption spectrum of brown carbon.
6. Identify sources, sinks, and atmospheric lifetime of brown carbon.
7. Field measurements in carbonaceous aerosol-dominated regions (e.g., North-Eastern India).

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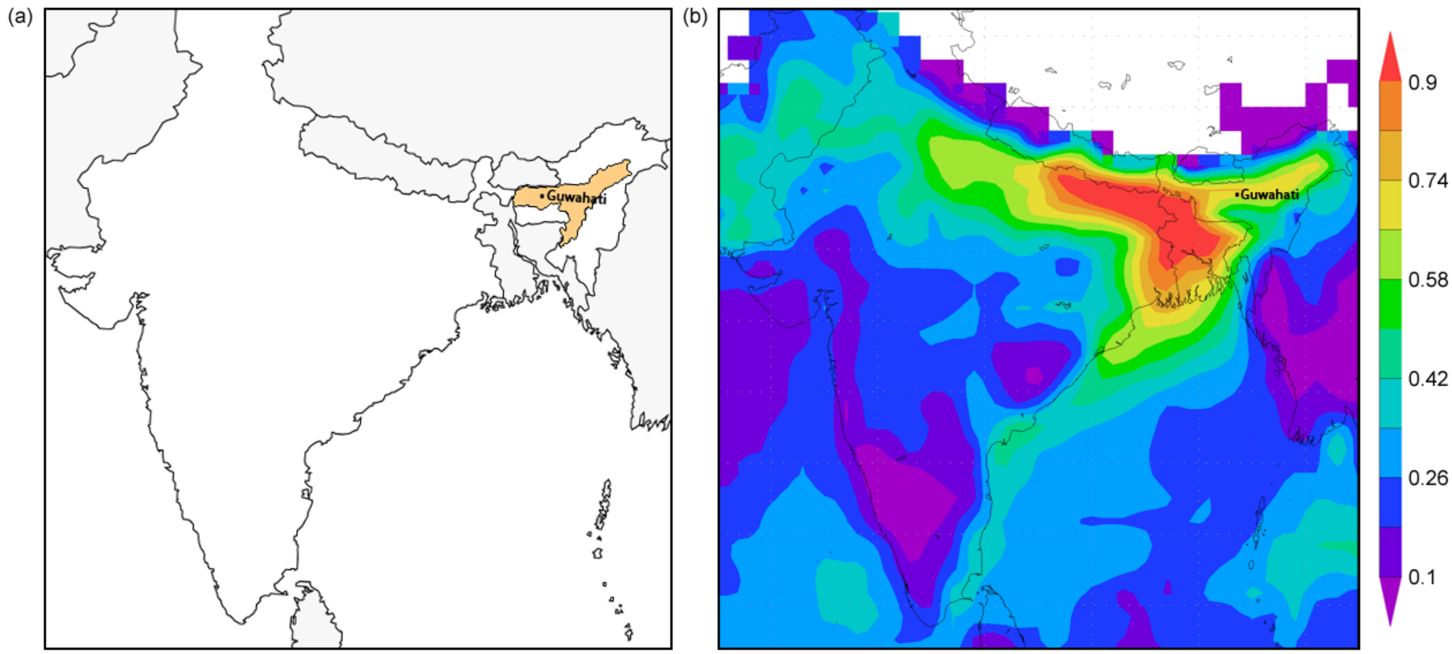
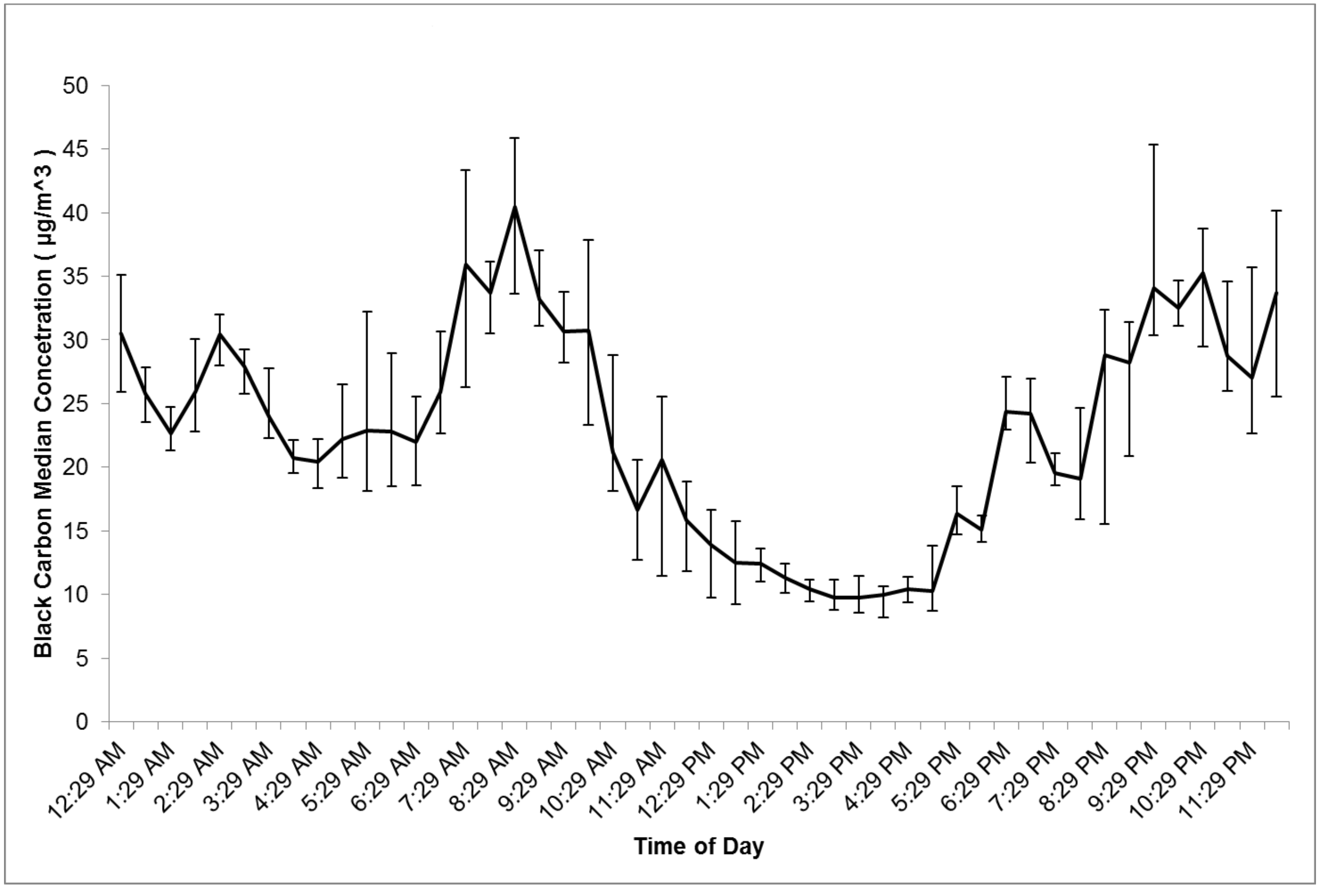
Carbonaceous Aerosols in North-Eastern India



MODIS TERRA monthly mean aerosol optical depth (AOD) over India for January 2011. Guwahati – The largest metropolis in the Northeastern region. Located in the Indo-Brahmaputra Basin.

- The northeastern region of India has been an unnoticed victim of extreme climate change.
- Main Causes: Industrialization and deforestation.
- The annual mean maximum temperatures are rising at the rate of +0.11°C per decade.
- The annual mean temperatures are increasing at a rate of 0.04°C per decade.
- The summer monsoon rainfall is found to be decreasing at an approximate rate of 11 mm per decade.
- No record of BC measurements available in Guwahati. No AERONET station nearby.

Exploratory Measurements



- BC mass concentration measured 27th Jan - 3rd Feb 2011 using a Micro-Aethalometer at 870nm.
- The daily median varied between 9-40μg/m^3
- Day-time concentration attributed mostly vehicular emissions, and night-time emissions due to open biomass burning (heating purposes and local religious activities)

BC mass concentration in Guwahati, India: **9 – 40 *μ*g/m³** is one of the highest when compared to major urban areas worldwide.

Location	Period	BC ($\mu g\ m^{-3}$)	Reference
Delhi, India	Dec	16.7	Singh et al. [2010].
Delhi, India	Feb	19	Beegum et al. [2009].
Hyderabad, India	Jan	21	Beegum et al. [2009].
Kanpur, India	Dec	6-20	Tripathi et al. [2005].
Kolkata, India	Annual	26.5	Chowdhury et al. [2007].
Mumbai, India	Jan – Mar	7.5 – 17.5	Venkataraman et al. [2002].
Bangalore, India Xi'an, China	Nov Jan	0.4 – 10.2 21.6	Babu et al. [2002]. Cao et al. [2007].
Urban, Europe	Dec – Feb	3.5 – 4.2	Putaud et al. [2003].
Maryland, USA (Suburban)	Annual	0.25 – 3	Chen et al. [2001].

Mineral Dust Aerosols

Al Asad (Western Iraq), 26-April-2005

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10 Soil Sample Locations

Bamako, Mali
Lanzarote, Spain
Djibouti
Khowst, Afghanistan
Qatar
UAE
Balad, Iraq
Tikrit, Iraq
Al Asad, Iraq
Coastal Kuwait

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Dust Suspension:

PM sampling and on-line optical measurements

Dust Suspension

$PM_{2.5}$ Size Selective Inlets

Photoacoustic Instrument with Scattering Sensor for SSA Measurement

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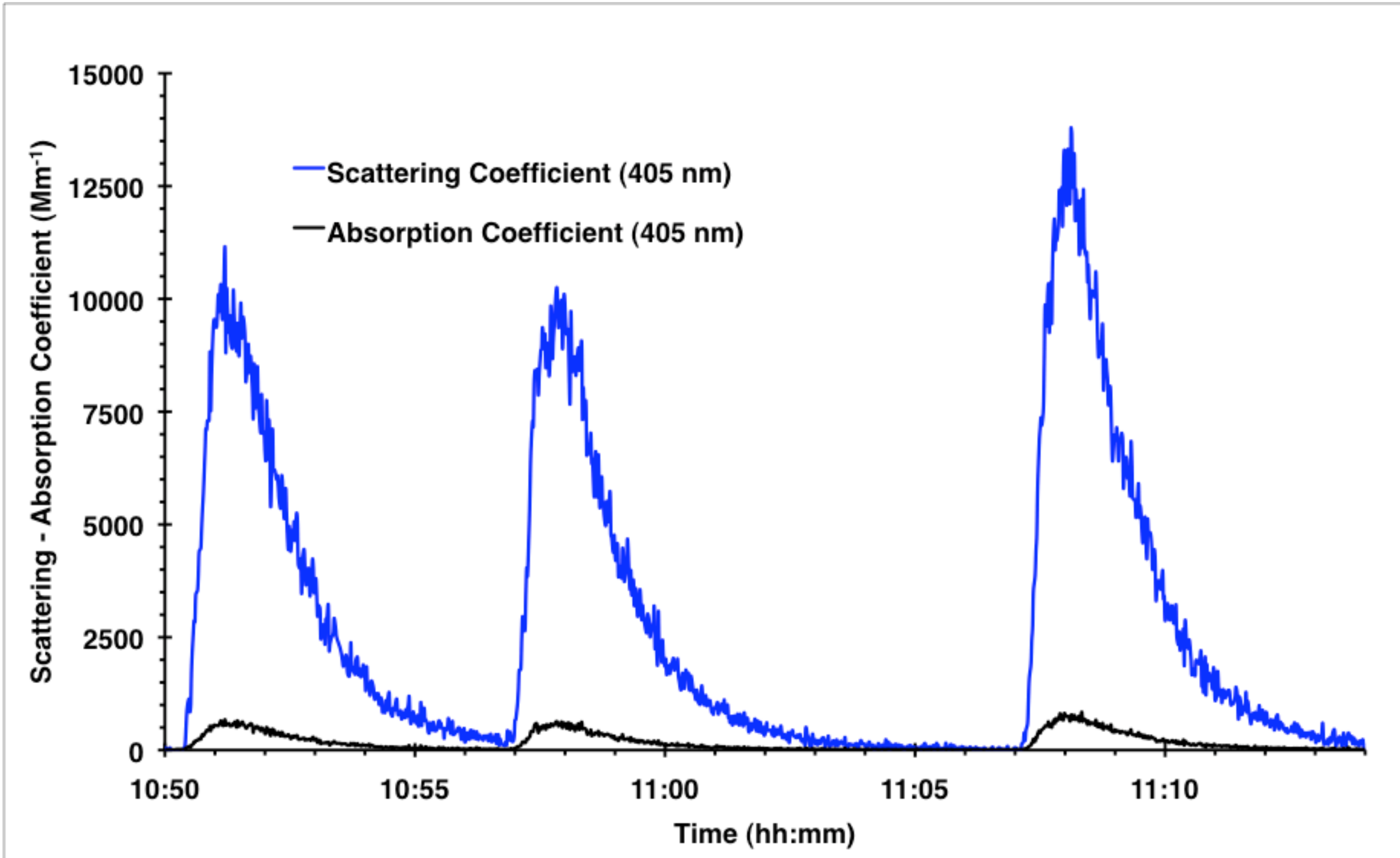
Raw Data Djibouti



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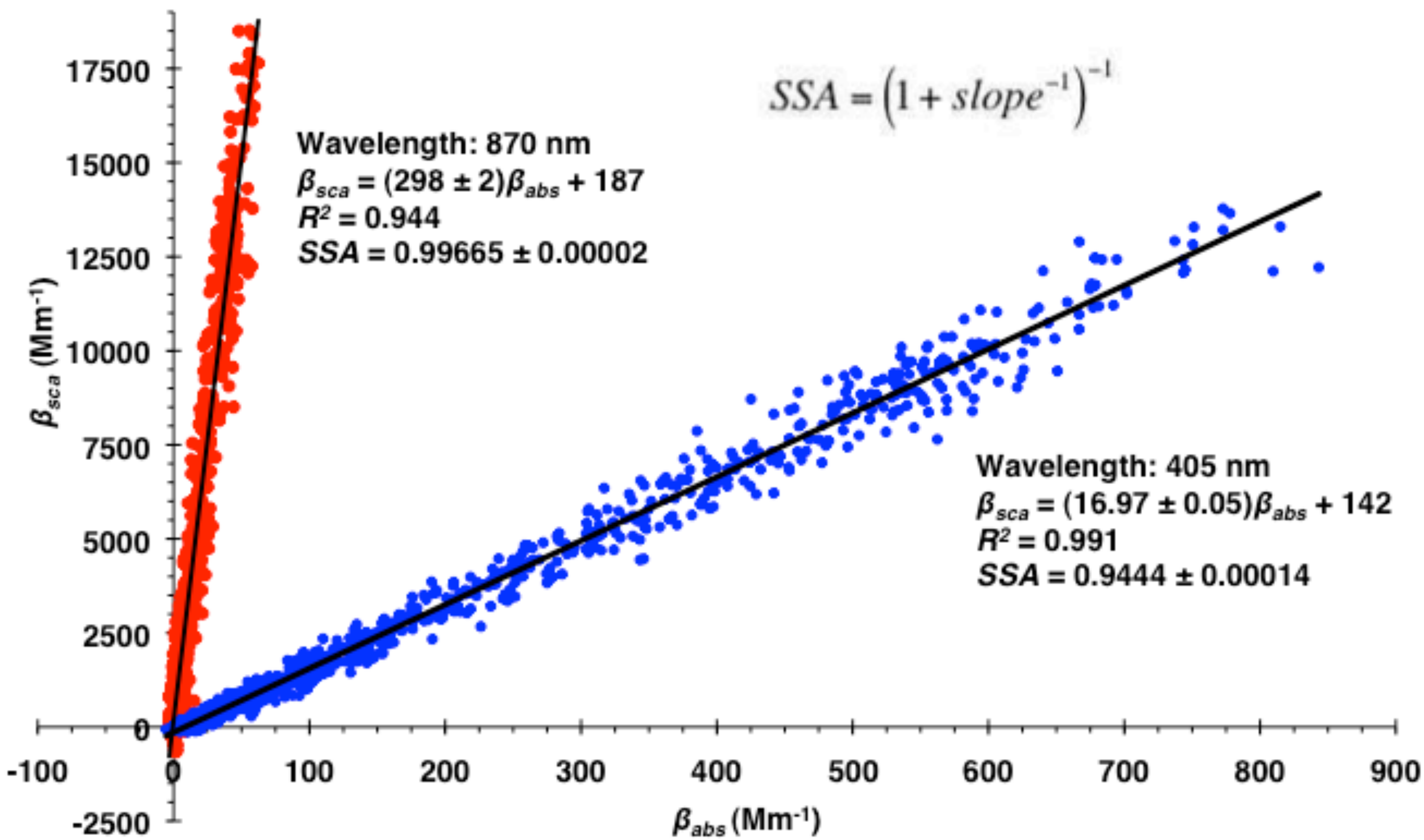
SSA Analysis (Djibouti)



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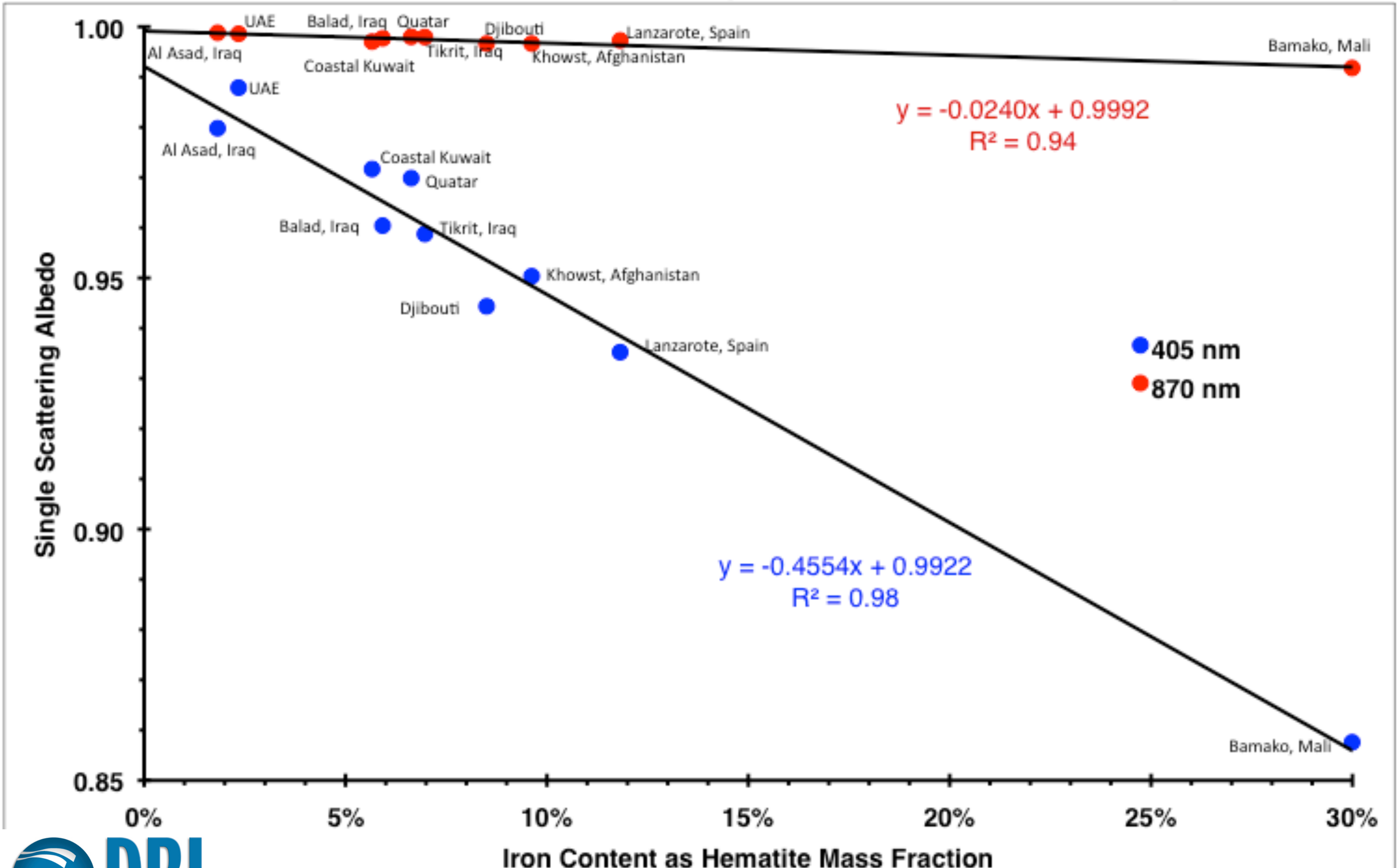
Results: SSA (Iron Content)



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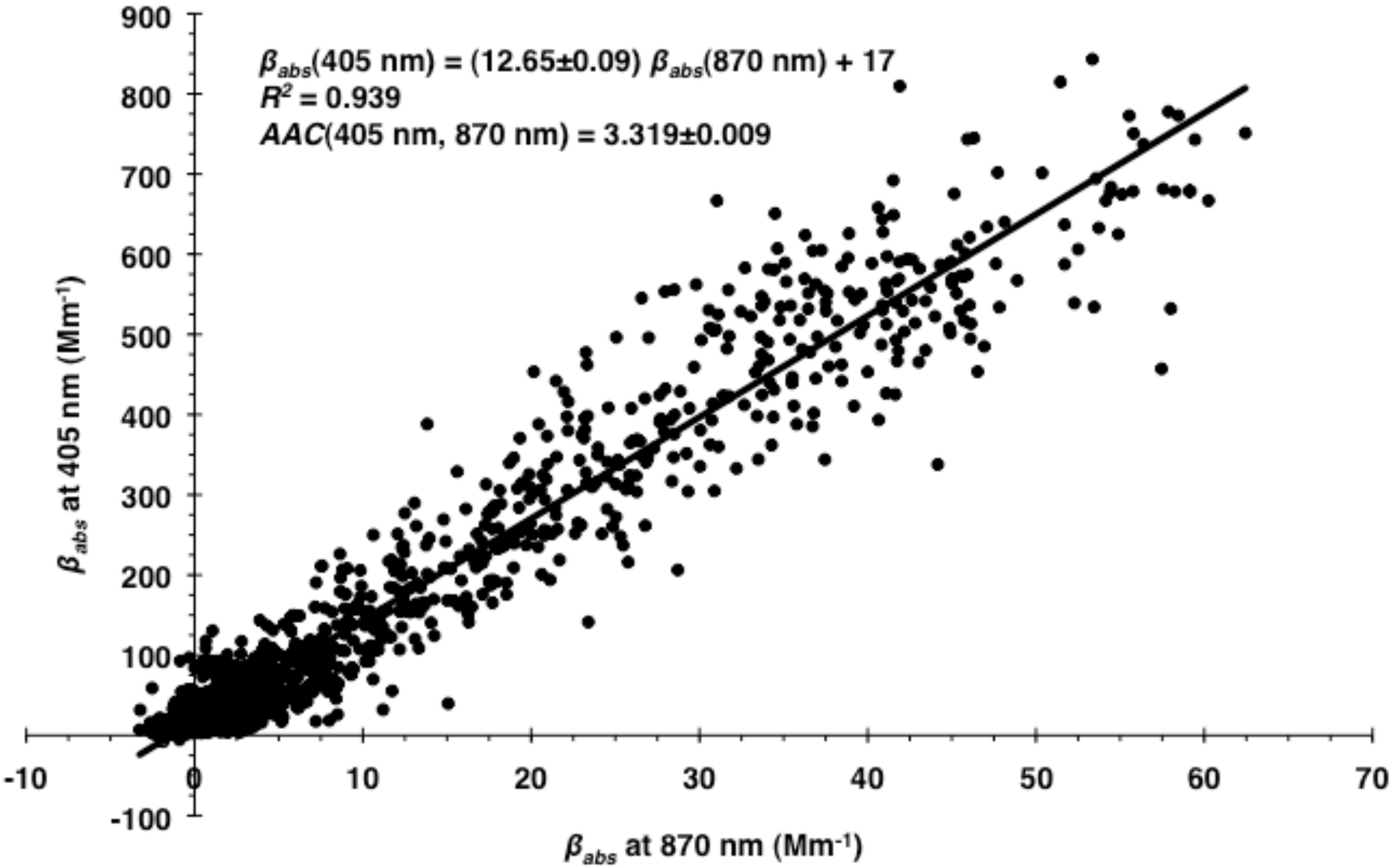
AAC Analysis (Djibouti)



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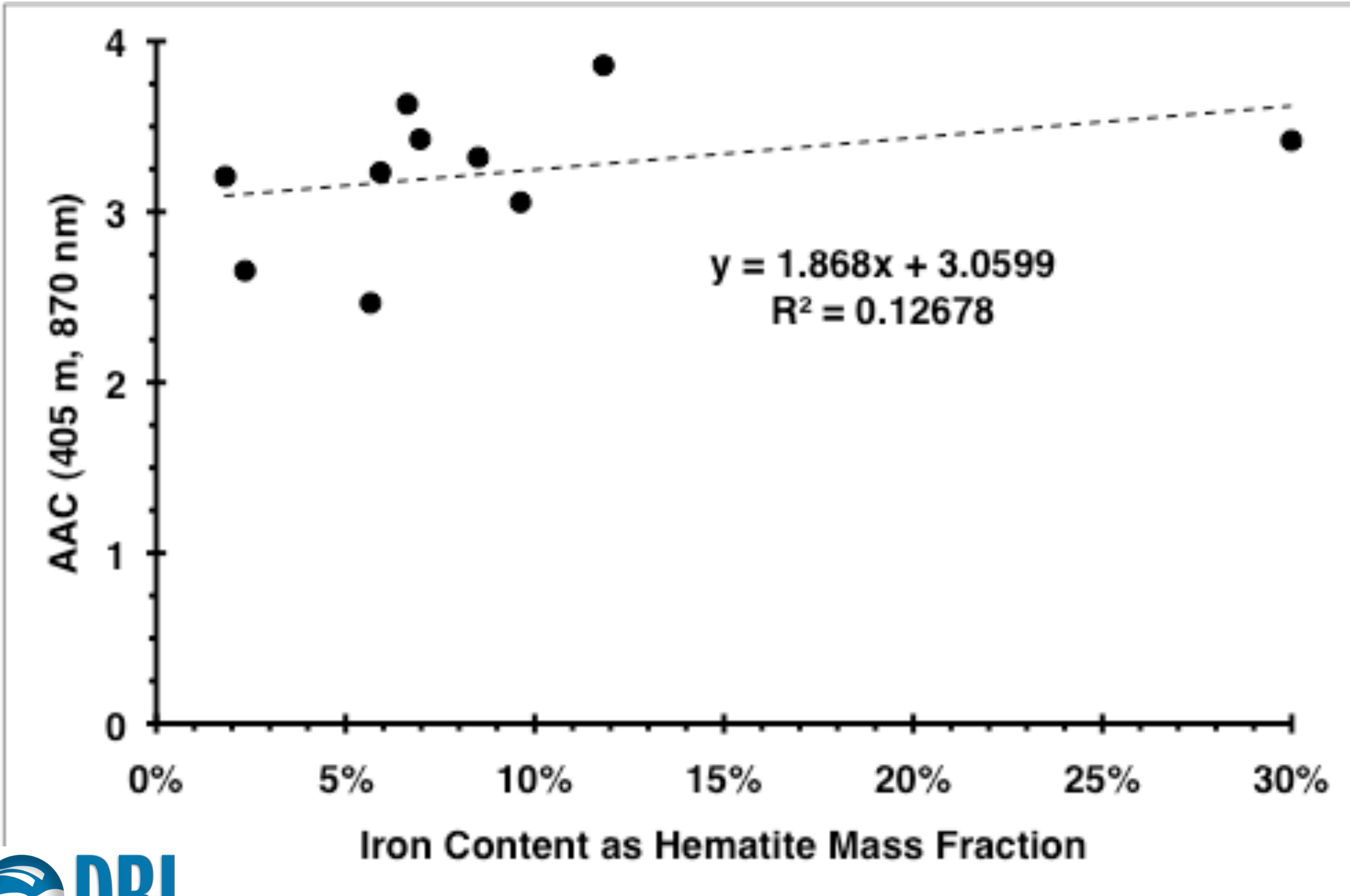
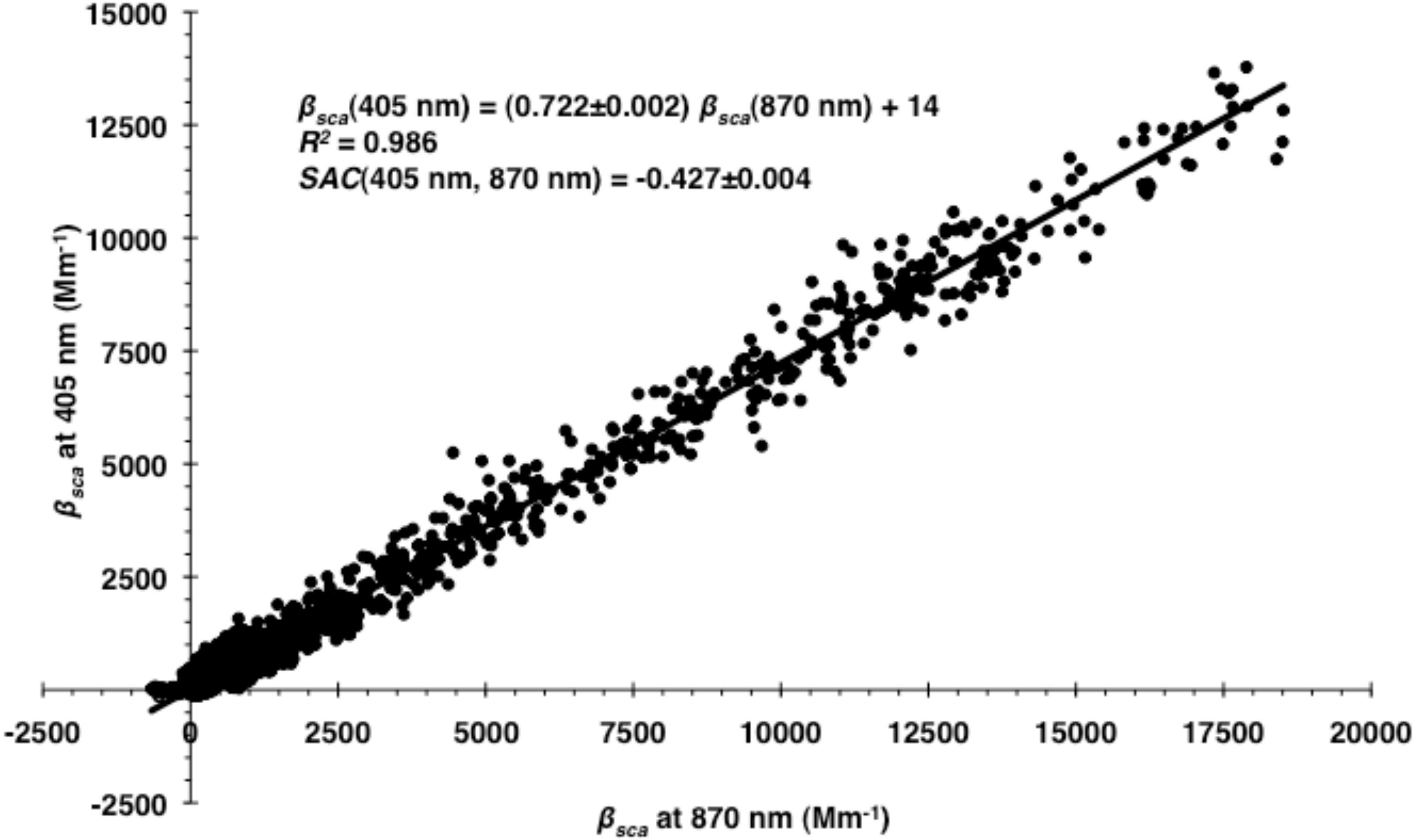
Results: AAC (Iron Content)



DRI
Desert Research Institute

SAC Analysis (Djibouti)



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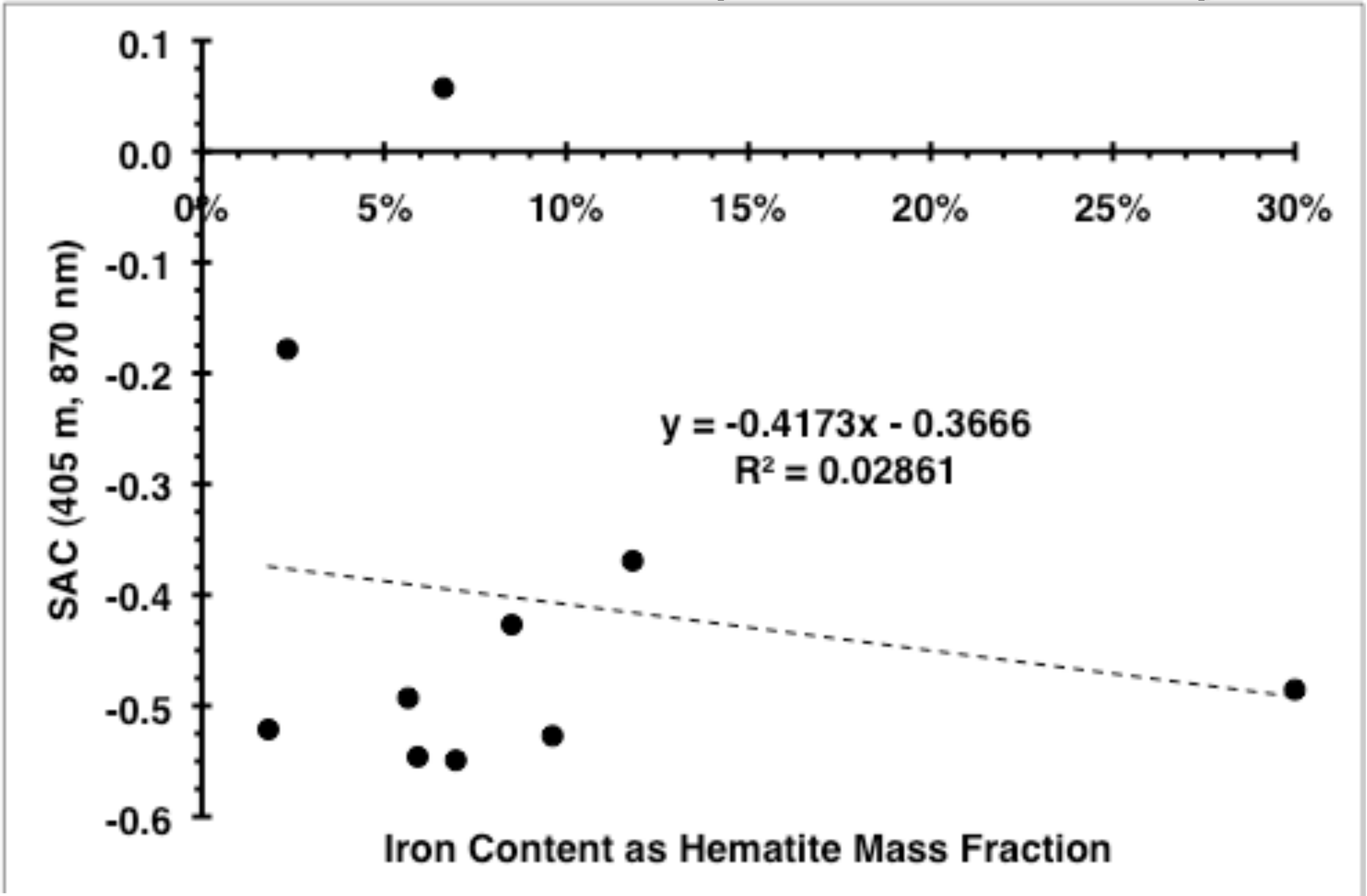
Results: SAC (Iron Content)



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Conclusions:

For our samples SSA is a linear function of iron content

1. Iron content can be determined from optical measurement. Satellite (Glory Mission) measurement of iron content?
2. SSA can be determined from chemical analysis for iron.
3. Negative SAC are common for hematite containing aerosols on Earth (and on Mars?) => blue sunsets?

Caution:

Limited set of samples, mostly from Arabian Peninsula and North Africa

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Moosmüller, H., J. Engelbrecht, W. P. Arnott, J. A. Gillies, and M. Skiba (2011). Single Scattering Albedo of Fine Mineral Dust Aerosols Controlled by Iron Concentration. *Geophys. Res. Lett.*, in preparation.

Current Work:

1. Measured SSA for 30 mineral dust samples and a pure hematite sample with three wavelengths photoacoustic-nephelometer instruments in collaboration with LANL (M. Dubey's group).
2. Acquired samples from the Bodélé Depression to be characterized.

Future Work:

1. Use new 4-wavelengths instrument
2. Obtain and analyze more samples from different locations
3. Do in-situ measurements of dust SSA and composition after long-range transport (Cape San Juan, Puerto Rico; collaboration with Olga Mayol-Bracero and John Ogren's group)

DRI
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THANK YOU FOR YOUR ATTENTION!

DO YOU HAVE ANY QUESTIONS?

(hansm@dri.edu)

Al Asad, Iraq